Stormwater Modeling for Flow Duration Curve Development in Vermont

Final Report
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1. INTRODUCTION

Numerous Vermont watersheds are not meeting Vermont's aquatic life standards because of stormwater runoff from suburban and urban drainages. As an effort to restore these watersheds, the state of Vermont has been engaged in many efforts, including a Docket to investigate the technical issues related to developing cleanup plans for impaired waters of the state by stormwater runoff (Docket No. INV-03-01). As a result of investigation processes, it was decided to understand and compare the hydrological conditions of the impaired (Figure 1.1 and Table 1.1) and attainment (Figure 1.2 and Table 1.2) watersheds and use them as surrogate indicators to identify appropriate control measures-especially using numerical targets to restore the impaired watersheds. The impaired watersheds are grouped into two categories, lowland (relatively flat) and mountain (steep) watersheds. Lowland watersheds were considered to be watersheds with an average elevation of less than 1,000 ft above mean sea level and the remainders were considered mountain watersheds. Among the impaired watersheds, only four watersheds fall under the mountain category and are not addressed in this report.

The state's ultimate goal is to restore the impaired watersheds to achieve water quality standards. If the water quality standard is a narrative one, like the aquatic life impairments in Vermont, the target must be developed by describing the desired level of aquatic life community or other related surrogates. Targets such as these include desired stormwater volume and peak flow reduction, pollutant reduction, or increase in ground water recharge. In these types of cases, the targets are generally developed by making comparison to one or more reference watersheds. The reference watershed should meet the water quality standard and designated use. The major assumption lying in the reference watershed approach is that the impaired water body would meet the water quality standards or designated use if the conditions at the impaired watershed were similar to that of the reference one. It was understood through previous investigations (Water Resources Board, 2004) that the aquatic life impairments addressed here are primarily due to the impacts of stormwater runoff from suburban and urban drainages. In these types of stormwater-related impairments, it is appropriate to use watershed hydrology as a surrogate target to address known and unknown stressors cumulatively (Saravanapavan et al., 2005).

Aquatic life impairment cannot be easily defined by a single event or an average stream hydrological condition. Typically, these types of impairments are a function of conditions that occur over an extended period of time (i.e., seasonally or annually). One way to enhance the understanding of habitat impairment is through a flow duration curve (FDC). FDC has been used as a tool to identify the ecological targets for rehabilitation of streams and rivers (Wiley et al., 1998). FDC shows the percentage of time during a period of record that flow exceeds a certain flow value. Usually FDC is developed using long-term flow records and represents the entire set of hydrological conditions such as events, seasons, and annual variations. In the absence of long-term flow records to generate FDC, computer models are widely employed to fill the data gap. This report presents the details of modeling efforts carried out to simulate long-term flow records to develop FDCs for selected impaired and attainment watersheds. Among the impaired watersheds, only four watersheds fall under the mountain category (Table 1.2) and are not addressed in this report. The study was performed with a continuous guidance and review of the study team (Appendix A) by incorporating the scientific expertise and local knowledge.

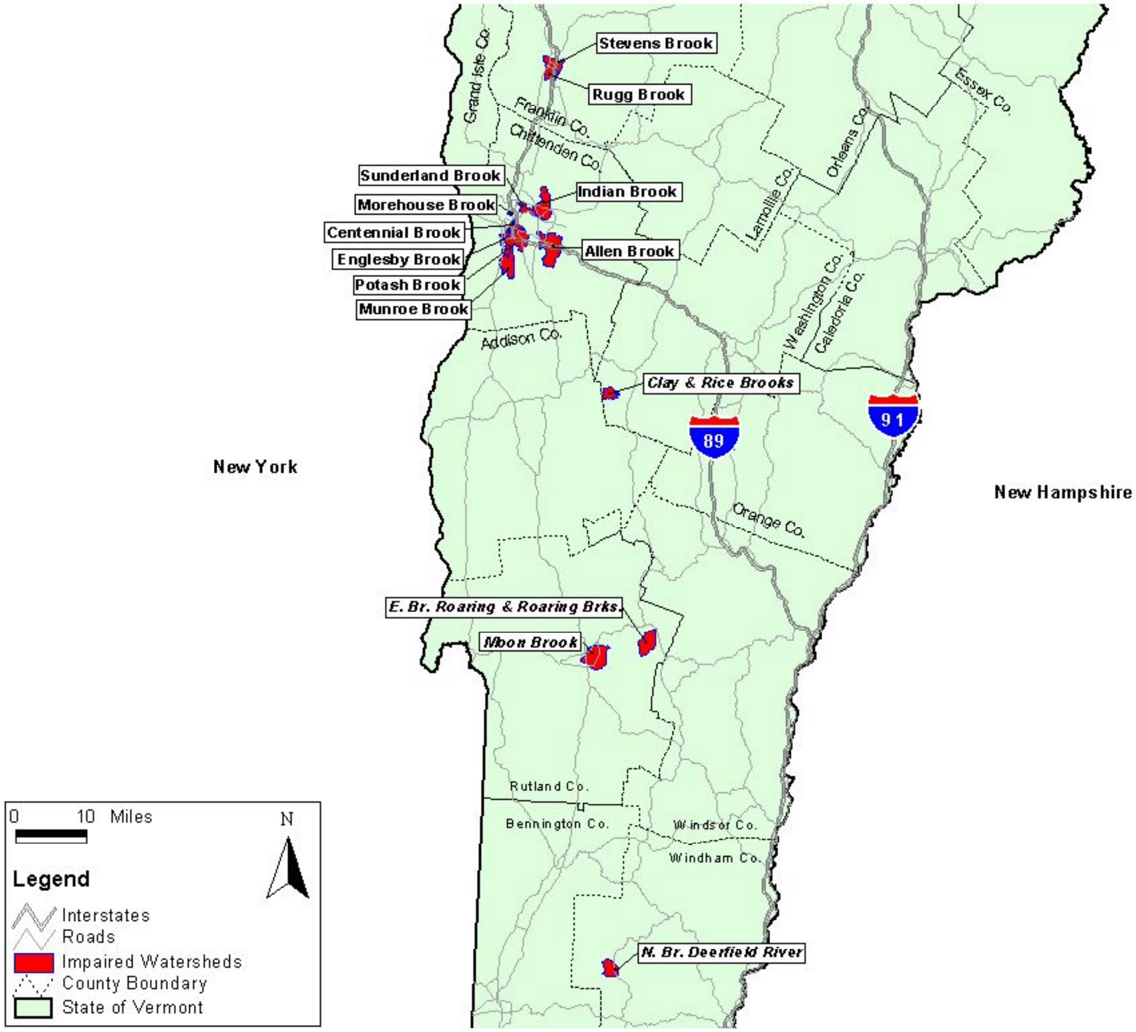


Figure 1.1. Aquatic life impaired watersheds in Vermont. Mountain watersheds, average elevation of 1000' or more from mean sea level, are in italic font.

Table 1.1. Impaired watersheds

Watershed	Area (Sq. miles)
Rugg Brook	2.86
Stevens Brook	3.33
Allen Brook	10.37
Bartlett Brook	1.15
Centennial Brook	1.43
Englesby Brook	0.85
Indian Brook	7.47
Moon Brook	*8.64*
Morehouse Brook	0.53
Munroe Brook	5.48
*N.Br. Deerfield Rive*r*	*5.58*
Potash Brook	7.42
*Rice Brook & Clay Brook**	*5.76*
*Roaring Brk & E.Br. Roaring Br**	*6.01*
Sunderland Brook	5.26

* Watersheds in italics are considered as Mountain watersheds.

Table 1.2. Attained watersheds

Watershed	Area (Sq. miles)
Allen Brook	3.90
Alder Brook	10.62
Muddy Branch New Haven River	13.90
Sheldon Spring Trib	2.99
Youngman Brook	1.35
Sand Hill Brook	1.27
Bump School Brook	1.08
Laplatte River	2.70
Hubbardton River	16.99
Teney Brook	4.86
Milton Pond Trib to Mallets Creek	2.55
Willow Brook	0.84
Little Otter Creek	20.54
Malletts Creek	15.02
Rock River	2.08

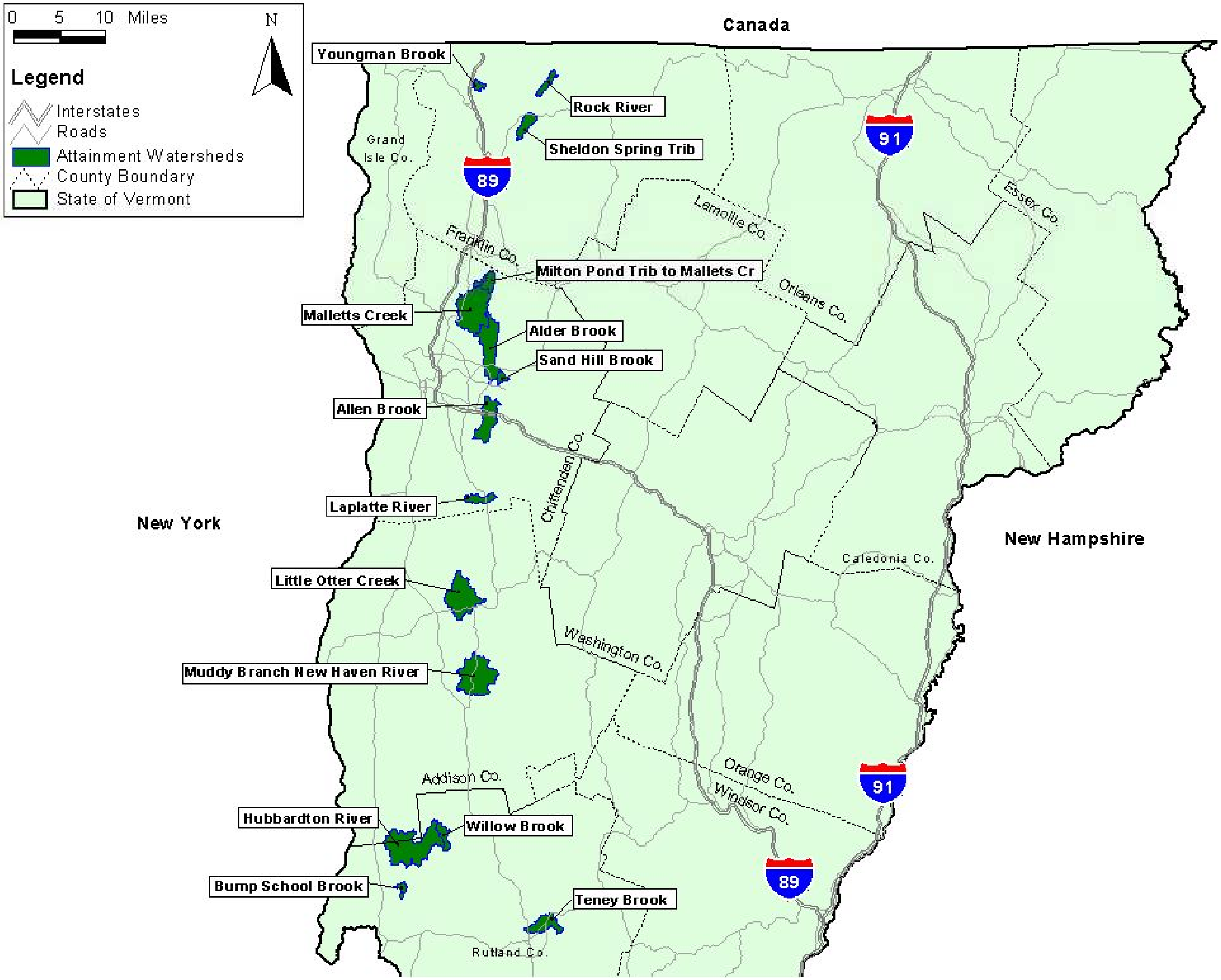


Figure 1.2. Aquatic life attainment watersheds in Vermont

In a modeling effort, it is important to select an appropriate model that the need for the modeling compromises with the available data and resources. Using available resources and requirements of the study, only mid-range models were considered for review and selection. Four different models were reviewed in detail to ascertain their appropriateness and P8 UCM model was selected for this study. **Section 2-Model Screening and Selection**, presents the details of model review and selection.

A review of input parameters of P8 UCM model and the model structures were conducted to appropriately apply the model to satisfy the study need and available data resources. An approach, including estimating model parameters from existing data, and other calibration needs, was developed and detailed in **Section 3–Model Setup**.

Model calibration is a critical and important part of the entire modeling effort. It involves testing and validating model structure and input parameters by comparing model simulation with actual observation. It also tests and validates the procedures of estimating input parameters so that the model can be successfully applied to ungauged impaired and attainment watersheds. The model was initially calibrated with daily flow observation of selected United States Geological Survey (USGS) flow gauges in the Lake Champlain watershed. The purpose of this calibration is to understand the model's capability in long tern changes such as seasonal variability, especially the time and the volume of snowmelting, and ground water recession during the drier period. **Section 4–Model Calibration with Daily Flow Data**, details the insight into the calibration task. Using the initial calibration, it was understood that the model set up had lacked in simulating ground water recession appropriately. To eliminate this drawback, a simple ground water estimation tool was developed. The details of the ground water enhancement, a simple linear reservoir model, are presented in **Section 5–Ground water Model Enhancement**. The enhanced model was further refined by calibrating the model with hourly flow observations of the University of Vermont (UVM) in and around Burlington. In this detailed calibration, major model parameters were verified by comparing the model simulations and observations. The details are presented in **Section 6–Detailed Model Calibration with Hourly Flow Data**.

Calibrated model was employed to simulate long term (ten year) hourly flow records for selected watersheds to generate FDCs. FDCs of selected impaired and attainment watersheds were reviewed to understand the appropriateness of setting surrogate hydrology targets. Selecting and setting stormwater control targets using FDC help to address the issues related to both dry- and wet-weather events on the basis of the conditions over a long-term period. While stressing the importance of addressing the issues associated with the entire hydrological domain, it is important to understand the control measures during the storm events, especially with a focus on implementing stormwater management solutions. The design and construction practices follow guidance and standards that are primarily set by the design storm events. The model was also applied to simulate flow during a design storm event to enhance the understanding of the target selection. **Section 7–Model Application**, documents the results of the model application, both FDC development and design storm analysis.

Finally, **Section 8–Conclusion and Discussion**, provides a look at how the modeling study meets its objectives and summarizes the capability of developed model.

2. MODEL SCREENING AND SELECTION

Available models to simulate long-term flow records range from simple to highly sophisticated. Simple models require little data, but lack the ability to simulate the realistic variability of the flow regime. On the other hand, sophisticated models are realistically capable in simulation, but the data needs are rarely achievable. Therefore, the model selection is a critical task in modeling studies. This section presents the evaluation and selection processes carried out in the study.

2.1 Model Requirements

The technical needs for a model to be employed in this study as identified by the study team are summarized below:

- Ability to simulate hydrologic response with a level of detail sufficient for analysis of stream flow and flow duration curve development
- Ability to perform reasonable model calibration
- Ability to simulate multiple urban pollutants, including sediment, nutrients (nitrogen and phosphorus), and metals, if necessary
- Ability to evaluate urban and mixed land uses, including pervious and impervious areas
- Consideration of short and long-term continuous periods as well as event-based simulation (i.e., single and multiple rainfall events)
- Consideration of commonly used stormwater best management practices (BMPs) at an equivalent level of resolution
- Consideration of BMPs at various locations in the watershed

Using available resources and requirements of the study, only the following mid-range models were considered for review and selection to ascertain their appropriateness:

- Generalized Watershed Loading Functions (**GWLF**)
- Source Loading and Management Model (**SLAMM**)
- Program for Predicting Polluting Particles Passage through Pits, Puddles, and Ponds (**P8**)–Urban Catchments Model (**UCM**)
- Stormwater Management Model (**SWMM**)-(Only RUNOFF and TRANSPORT blocks)

2.2 Model Screening

In an urban or a suburban condition, simulation from drainage area, flow through reaches and stormwater conveyance systems, and flow through stormwater management facilities are important elements to be considered. Several factors were identified as being important for evaluating available watershed models in the study:

- At what spatial scale (i.e., cell, field, catchment, sub watershed, or watershed) is the modeling application most suitable?
- At what time scale (i.e., continuous or event-based) is the simulation performed, and what is the minimum applicable computation time step?
- What land uses (urban and non-urban) can be simulated? Are point sources addressed?
- How capable are its algorithms for hydrology simulation? Specifically, how is the rainfall-runoff simulation performed? How is ground water interaction/baseflow simulation considered? Is snowmelt considered?
- How capable are its algorithms for water quality (pollutant loading) simulation? Specifically, how does it address sediment, nutrients, and other pollutant loading generation, transport, and transformation?

- The evaluation results are summarized in Table 2.1. These factors are closely aligned with the four major categories of simulation needs (i.e., land, reach, conduit, and BMP).

Table 2.1. Watershed model evaluation summary.

Criteria		SWMM	P8 UCM	SLAMM	GWLF
Land uses	Urban	●	●	●	◖
	Rural	◖	○	○	●
	Point sources	●	●	●	○
Time scale	Continuous	●	●	●	●
	Event-based	●	●	●	
	Time step (input data /processes)	V	Hour	V	Day
	Time step (output)	V	Day	V	Month
Hydrology	Runoff	●	●	●	●
	Flow routing (in-stream)	●	○	○	
	Baseflow	●	○	○	○
	Snowmelting	◖	◖		◖
Pollutant loading	Sediment	●	●	●	●
	Nutrients	●	●	●	●
	Metals	●	●	●	
	Other	●	●	●	
Pollutant routing	Transport	◖	◖	◖	○
	Transformation	○			
Operation unit		CM/Cell	CM	CM	Wsh
Public domain		Y	Y	Y*	Y
Level of effort required		◖	◖	◖	○

● = Model addresses/simulates the factor with a high level of details. ◖ = Model addresses/simulates the factor with a medium level of details. ○ = Model addresses/simulates the factor with a low level of details. If the space left blank, it is not incorporated in the model.

V Variable simulation time step (down to hourly or sub-hourly).
CM Catchment: capable of simulating multiple watersheds and sub-watersheds.
Cell Watershed area represented as a network of cells. Flow is routed from cell to cell.
Field Limited to small single simulation unit, typically a field or monitoring plot.
Wsh Watershed: Limited to single watershed simulation.
* - WinSLAMM, the latest version with graphical user interface, is not public domain software.

The following factors were also considered regarding BMP modeling capabilities:

- What pollutant removal processes and mechanisms are simulated?
- What algorithms are applied for flow routing and pollutant removal process simulation?
- What types of BMPs can be addressed?

The evaluation results are summarized in Table 2.2. GWLF model was excluded in the comparison, as it has no BMP evaluation capabilities.

Table 2.2. Summary of BMP capabilities

Model	BMPs	Process/Mechanisms	Algorithms
SWMM	• Detention basin • Infiltration practices • Street sweeping • Catch basin cleaning	• Overland flow • Storage • Infiltration • Overflow/outlet flow • Settling/decay • Flow routing through natural and man made channels	• Linear reservoir • Horton and Green-Ampt • Buildup/washoff
P8 UCM	• Detention basin • Infiltration practices • Swale/buffer strip • Manhole/splitter • Street sweeping	• Overland flow • Storage • Infiltration • Overflow/outlet flow • Settling/decay • Shallow flow routing	• SCS curve number • Linear reservoir • Green-Ampt • Second-order decay • Particle removal scale factor
SLAMM	• Detention basin • Infiltration practices • Swale/buffer strip • Porous Pavement • Biofiltration/raingardens • Cisterns/rain barrels • Street sweeping • Catch basin cleaning	• Overland flow • Storage • Infiltration • Overflow/outlet flow • Settling/decay	• Improved small storm hydrology model (Pitt, 1987) • Buildup/washoff

2.2.1. SWMM

The Stormwater Management Model (SWMM) is a dynamic rainfall-runoff simulation model developed by EPA primarily, but not exclusively, for urban areas for single-event or long-term (continuous) simulation using various time steps (Huber and Dickinson, 1988). It was initially developed to address urban stormwater issues and help with storm event analysis and derivation of design criteria for structural control of urban stormwater pollution. It was later upgraded to allow for continuous simulation of and applications to complex watersheds and land uses. Several modules or blocks are included to model a wide range of watershed quality- and quantity-related processes. The model has been widely used for analysis of hydrologic and hydraulic problems attributed to both combined and separate sewer systems and for urban nonpoint pollution problems. SWMM simulates real storm events on the basis of meteorological data and catchments, transport, storage, and treatment characterization.

Model output consists of "quantity and quality" analysis ("quantity" being hydrographs and runoff volumes and "quality" being pollutant loads). Single events and continuous simulation can be performed for any values of rainfall, runoff, and quality cycles for a watershed. The interstorm interval, however, is treated simplistically, with the most significant processes being continuous infiltration into baseflow and buildup of contaminants on impervious surfaces. The most common application of SWMM is to analyze isolated storm events.

In SWMM, the RUNOFF block simulates the land processes. The basic spatial unit for SWMM is the subcatchment, into which the modeled watershed is subdivided. The infiltration calculation method is selected by the user and uses either the Horton or Green-Ampt methods. A version of Manning's equation is used to estimate flow from the subcatchment area based upon a conceptual model of the sub-catchment as a "nonlinear reservoir." The lumped storage scheme is applied for soil/ground water modeling. For impervious areas, a linear formulation is used to compute daily/hourly increases in particle accumulation. For pervious areas, a modified Universal Soil Loss Equation (USLE) determines sediment load, and pollutant loading is estimated using a potency factor.

Flow routing is performed for surface and subsurface conveyance and ground water systems, including the option of fully dynamic hydraulic routing. The SWMM TRANSPORT block includes kinematic wave routing of flow and quality, base flow generation, and infiltration capabilities, and it routes flow through user-defined systems ranging from natural channel to concrete pipes. A more complex and highly parameterized routing module, EXTRAN, is also available, and it carries out a numerical solution of the complete St. Venant equations for urban drainage ways and conduits by modeling the network as a link-node system.

For the purpose of this study, the RUNOFF and TRANSPORT blocks of SWMM have been considered for comparison with other mid-range models. In relation to the need of this project, strengths and weaknesses of SWMM are listed below:

<u>Strengths:</u>

- Continuous simulation
- Physically based hydrograph development
- Snowmelt and baseflow simulation
- Flow routine
- Variable time step in hourly or sub-hourly simulation

<u>Weaknesses:</u>

- Input data, parameterization, and calibration require extensive effort
- All information needed to set up, calibrate, and validate the model are not readily available
- Limited stormwater BMP capabilities

2.2.2. P8 UCM

The Program for Predicting Polluting Particles Passage through Pits, Puddles, and Ponds, Urban Hatchment Model (P8 UCM), is used to model generation and transport of stormwater runoff pollutants in an urban setting (Walker, 1990). Continuous water balance and mass balance calculations are performed on a user-defined system consisting of watersheds, devices (runoff storage/treatment areas, BMPs), particle classes, and water quality components. Simulations are driven by continuous hourly rainfall and daily air temperature time series data. Primary applications are the evaluation of site plans for compliance with treatment objectives expressed in terms of removal efficiency for Total Suspended Solids (TSS), and BMP design to achieve treatment objectives. Secondary (and less accurate) predictions from this model are runoff quality, loads, violation frequencies, water quality impacts due to proposed development, and generating loads for driving receiving water quality models (Walker, 1990). The model simulates pollutant transport and removal in a variety of treatment devices (BMPs), including swales, buffer strips, detention ponds (dry, wet, and extended), flow splitters, and infiltration basins (offline and online), pipes, and aquifers. Water quality components include TSS (five size fractions), total phosphorus (TP), total Kjeldahl nitrogen (TKN), copper, lead, zinc, and hydrocarbons.

Methods applied in P8 UCM include: Soil Conservation Service's (SCS) curve number technique, linear reservoir storage routing, second-order reactions, and particle removal by use of a scale factor. Runoff from pervious areas is computed using the SCS curve number method. Antecedent moisture conditions are adjusted using 5-day antecedent precipitation and season. Percolation from pervious areas is estimated by water balance at the surface (percolation = precipitation – runoff-evapotranspiration).

Evapotranspiration is computed from air temperature and season using Hamon's method (Hamon, 1961). Runoff from impervious areas starts after the cumulative storm rainfall exceeds the specified depression storage. Both rainfall and snowmelt are considered in runoff estimations. Particle concentrations in runoff from pervious areas are computed using a method similar to the sediment-rating curve included in SWMM. Particle loads from impervious areas are computed using either or both of two techniques:

- Particle accumulation and washoff
- Fixed runoff concentration.

The first method is used in default particle datasets. An exponential washoff relationship similar to that employed in SWMM is used to simulate particle buildup and washoff from impervious surfaces.

Receiving water simulation is limited to devices, ponds, infiltration basins, and shallow channels. Storage area or volume and outflow relations represent flow in ponds. Shallow channel flow is estimated by using the Manning equation. Settling and transport of sediments are also simulated in the model. Because the P8 UCM model estimates surface runoff at an hourly time step using the SCS curve number approach, it requires substantial calibration. In relation to the need of this project, strength and weaknesses of P8 are listed below:

<u>Strengths:</u>

- Continuous simulation
- Snowmelt and baseflow simulation
- Urban stormwater BMPs and wetland simulation
- Data needs can be filled with available information
- Requires moderate effort to set up, calibrate, and validate the model

<u>Weaknesses:</u>

- SCS curve number approach at hourly time step requires substantial calibration
- Limited capability in flow and pollutant routing

2.2.3. SLAMM

The Source Loading and Management Model (SLAMM) was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality (Pitt, 1993). It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales). SLAMM was developed with the heavy use of actual field observations with minimal reliance on pure theoretical processes that have not been adequately documented or confirmed in the field. The model performs continuous mass balances for particulate and dissolved pollutants and runoff volumes. Runoff is calculated using a method developed by Pitt (1987) for small-storm hydrology. Runoff is rainfall minus initial abstraction and infiltration is calculated for both impervious and pervious areas. Triangular hydrographs, parameterized by a statistical approach, are used to simulate flow. Exponential buildup and rain washoff, as well as wind removal functions are used for pollutant loading estimation. Water and sediment from various source areas are tracked as they are routed through treatment devices. SLAMM is mostly used as a planning tool to better understand sources of urban runoff pollutants and their control.

One of SLAMM's most important features is its ability to consider many stormwater controls (affecting source areas, drainage systems, and outfalls) for a long series of rain events. The program considers how particulates filter or settle out in control devices. Particulate removal is calculated according to the design characteristics. Storage and overflow of devices are also considered. At the outfall locations, the characteristics of the source areas are used to determine pollutant loads in solid and dissolved phases. SLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters to better predict the actual range of outfall conditions (especially pollutant concentrations).

SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rainfall events, development characteristics, and control practices. Like all stormwater models, SLAMM needs to be accurately calibrated and then tested (verified) as part of any local stormwater management effort. SLAMM heavily uses a statistical approach with currently available field observations; therefore, it is not a process-based model. When applying the model in a different geographic or hydro-climatic conditions, it may not represent local conditions appropriately. Other drawbacks of SLAMM are that the model does not simulate snowmelt and base flow processes. In relation to the need of this project, strengths and weaknesses of SLAMM are listed below:

<u>Strengths:</u>

- Better representation of hydrograph for small storms
- Source areas can be evaluated separately
- Variable time step hourly or sub-hourly simulation
- Urban stormwater BMPs and wetland simulation
- Data needs can be filled with available information
- Requires moderate effort to set up, calibrate, and validate the model

<u>Weaknesses:</u>

- No snowmelt simulation capability
- No continues simulation of baseflow, therefore, limited to storm events
- No flow and pollutant routing capability

2.2.4. GWLF

The Generalized Watershed Loading Functions (GWLF) model was developed at Cornell University to assess the point and nonpoint source loading of nitrogen and phosphorus from urban and agricultural watersheds, including septic systems, and to evaluate the effectiveness of certain land use management practices (Haith et al., 1992). One advantage of this model is that it was written with the express purpose of requiring no calibration, making extensive use of default parameters. The GWLF model includes rainfall-runoff, erosion, and sediment generation components, as well as total and dissolved nitrogen and phosphorus loadings. The rainfall-runoff process is simulated using the curve number method, and sediment erosion is simulated using the USLE method. It simulates and tracks nutrients in both particulate form (combined with sediment) and dissolved form. The model uses daily time steps and allows for analysis of annual and seasonal time series. The model also uses simple transport routing, on the basis of the delivery ratio concept. In addition, simulation results can be used to identify and rank pollution sources and evaluate basin-wide management programs and land use changes. In relation to the need of this project, strengths and weaknesses of GWLF are listed below:

Strengths:
- Source areas can be evaluated separately
- Data needs can be filled with available information
- Requires moderate effort to set up, calibrate, and validate the model

Weaknesses:
- Output limited to monthly scale that is insufficient to develop accurate flow duration curve
- No flow and pollutant routing capability
- No simulation of flow and pollutants through BMPs
- No representation of a stream network

2.3 Model Selection

The selected models were screened according to the project needs, data availability, and the level of effort required by employing a scoring system. To facilitate a cross comparison, a scoring system was introduced. The highest score of 3 represents high level of support, and the lowest score of 0 represents no support. The summary of the screening is presented in Table 2.3.

Table 2.3. Summary of the scores for selected models

Screening consideration	SWMM	P8 UCM	SLAMM	GWLF
Continuous simulation	2	2	0	2
Time step to generate flow duration curve	3	2	3	0
Hydrograph development	3	2	3	2
Baseflow/ground water simulation	1	1	0	1
Snowmelt simulation	2	2	0	2
Flow and pollutant routing	2	1	1	0
Representing stream network	3	2	1	0
Stormwater BMP simulation	1	3	3	0
Source area evaluation	1	1	3	2
Data need and availability	1	2	2	3
Level of effort required	1	2	2	2
Total Score	**20**	**20**	**18**	**14**

3 High level of support, 2 Moderate level of support, 1 Low level of support, 0 No support

Using the total scores, both the SWMM (only RUNOFF and TRANSPORT blocks) and P8 UCM models scored the highest score of 20. SWMM has its strength in hydrological and routing capabilities while P8 UCM has its strength in simplicity and BMP evaluation.

Although SWMM is better than P8 UCM in hydrological and routine capabilities, it relies on many parameters that cannot be determined from existing data and require professional judgments and assumptions. It may easily create uncertainties among stakeholders. In addition, the SWMM model requires extra effort that could result in limiting the number of watersheds to be analyzed due to the budget constrain. On the other hand, P8 UCM, with reasonable calibration, will generate continuous data to develop flow duration curves. The data required to develop P8 UCM model is readily available. The model can also be used to simulate many urban pollutants as well as urban BMPs. In addition, improvement and modification to the P8 UCM model is relatively easy.

On the basis of the scientific objectives of this study, the number of watersheds for which analysis is required, available budget, and the intended future use of the models by the state, Tetra Tech recommended P8 UCM.

3. MODEL SETUP

Model setup is the process of presenting watershed characteristics into model parameters. It is important to appropriately set up the model, defining the model structure, and estimating input parameters to satisfy the study need and available data resources. This section details a review of input parameters of P8 UCM model and the model structures and presents an approach to estimate model parameters from existing data and other calibration needs.

3.1 Model Structure

When employing the P8 UCM model to watershed-scale application, surface runoff and baseflow are routed to the watershed outlet with different time of concentrations (TC). One is for the ground water base flow (TC-BF) and the other is for the surface runoff (TC-SR). TC-BF can be defined as the time between infiltration and when it reaches the stream (and is thus different from the traditional hydrological definition for TC). TC-SR is the same as the traditional definition of hydrological TC, i.e., the time runoff takes to travel from the farthest point in the watershed to the watershed outlet. Surface runoff from a watershed is first directed to a pipe device and then directed to another pipe device (watershed outlet). Percolation or infiltration from a watershed is first directed to an aquifer device that directs ground water flow (base flow) to the watershed outlet using a time lag (Walker, 1990). Figure 3.1, illustrates a sample schematic diagram for a simple representation of a watershed. The outlet device generates the total stream flow at the outlet of a watershed. Other devices such as detention ponds, wetlands, and possibly flow routing can be introduced to the model.

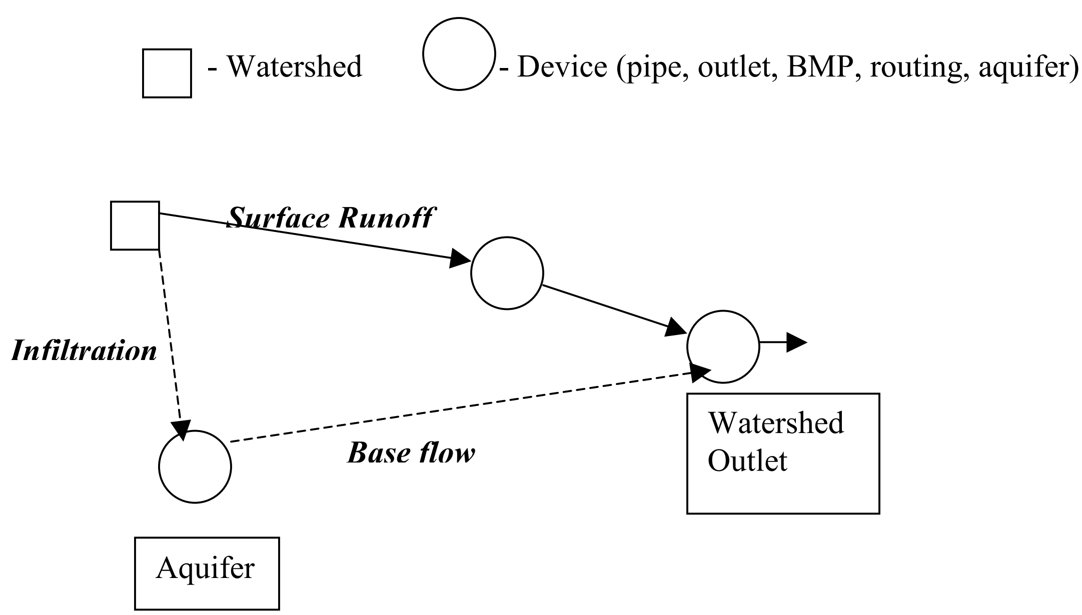


Figure 3.1. Sample schematic diagram for a watershed in P8 UCM model

3.2 Input Parameters

In P8, simulations are driven by continuous hourly rainfall and daily air temperature time series data. The model is capable of simulating flow (and water quality) from watersheds with variable land uses on an hourly time step. The model estimates runoff for pervious and impervious portions of a watershed separately. To determine the pervious and impervious areas of each watershed, percent imperviousness values were used (on the basis of land use in the watershed). Total drainage area, percent imperviousness, impervious runoff coefficient, and depression storage are the input parameters needed to estimate runoff from impervious potion of a watershed. Pervious curve number, along with total drainage area, is the important input parameter to estimate runoff from pervious portion of a watershed. The following subsections detail the input model parameters.

3.2.1. Percent Imperviousness

P8 UCM has two input parameters that specifically relate to surface runoff from impervious areas, percent imperviousness (PI) and the Imperviousness Runoff Coefficient (IC). PI was estimated using a previously developed relationship (CWP et al., 1999) for the Vermont Center for Geographic Information (VCGI) land use data layer. Table 3.1, presents the relationship between land use and percent imperviousness. Gaddis and Bowden (2005) analyzed these relationships and found that the approach was appropriate to apply to estimate watershed PI. The IC parameter is used to translate total watershed impervious area into directly connected or effective impervious area. Directly connected or effective impervious area represents the portion of watershed's impervious area that drains directly to the stream. IC ranges from 0 to 1. If the imperviousness in a watershed completely connected to the stormwater conveyance system, IC is 1. In this model application, PI was estimated using Table 3.1 and IC was set as a calibration parameter.

Table 3.1. Relationship between VCGI land use and percent imperviousness

VCGI land use code	Land use name	Percent impervious cover
3	Brush/Transitional	0%
5	Water	0%
7	Barren Land	0%
11	Residential	14%
12	Commercial	80%
13	Industrial	60%
14	Transportation	41%
17	Other Urban	60%
24	Agriculture/Mixed Open	2%
41	Deciduous Forest	0%
42	Coniferous Forest	0%
43	Mixed Forest	0%
62	Non-Forested Wetland	0%
211	Row Crops	2%
212	Hay/Pasture	2%

3.2.2. Pervious Runoff Curve Number

P8 UCM uses the curve number (CN) approach for hydrologic simulation of pervious areas. As such, weighted CNs for the pervious portions of each watershed was estimated using VCGI land use and Soil Survey Geographical (SSURGO) soils data. Table 3.2, presents CNs used for each land use/soil group combination in the study.

Table 3.2. CNs for land uses

Land use	CN for hydrology soil group			
	A	B	C	D
Pervious portion of urban land uses (residential, commercial, industrial, transportation, etc.) – Urban open space in good condition	39	61	74	80
Brush/transitional (assuming fair condition)	35	56	70	77
Barren land (assuming natural desert landscaping)	63	77	85	88
Agriculture/mixed open	30	58	71	78
Forest (all types in fair condition)	36	60	73	79
Non forested wetland (as per MA NRCS)	78	78	78	78
Row crops (assuming contoured + crop residue cover in good condition)	64	74	81	85
Hay/pasture (assuming fair condition)	49	69	79	84

(Source: USDA, 1986)

3.2.3. Other Model Parameters

In the impervious portion of a watershed, the surface runoff starts after the cumulative storm rainfall exceeds the specified depression storage. The depression storage was presented as a function of watershed average slope (Walker, 1990) as in Table 3.3.

Table 3.3. Depression storage and watershed slope relation

Watershed Slope (%)	Depression Storage (inch)
0.5	0.042
1	0.030
2	0.021
3	0.018
4	0.015
5	0.014

The table was based on the following relationship (Kidd (1978) as referred by Walker (1990)).
Depression Storage (in) = 0.03 X Slope$^{-0.49}$

Time of concentration values (TC-SR & TC-BF) were set as calibration parameters and are detailed in Sections 4 and 6. Other watershed characteristics, such as watershed area and slope, were directly estimated from geographic information system (GIS) data available from the Department of Environmental Conservation (DEC) and VCGI (site: web address).

4. MODEL CALIBRATION WITH DAILY FLOW DATA

The purpose of this calibration is to understand the model's capability to simulate long-term changes including seasonal variability, time and the volume of snowmelt, and ground water recessions during dry periods.

Watersheds in Vermont and eastern New York within the Lake Champlain watershed and with available flow data (USGS gauge data) were evaluated to identify watersheds of similar size (i.e., drainage area) to the impaired and attained watersheds. Watersheds (Figure 4.1 & Table 4.1) with gauging data were used to support hydrologic calibration. Note that both watersheds selected for the calibration are in New York. This is due the absence of appropriate watersheds in Vermont with long-term flow data at the time of calibration. Selection of the two calibration watersheds in New York was considered appropriate because both are in the Lake Champlain watershed and have similar watershed characteristics such as land cover and soil.

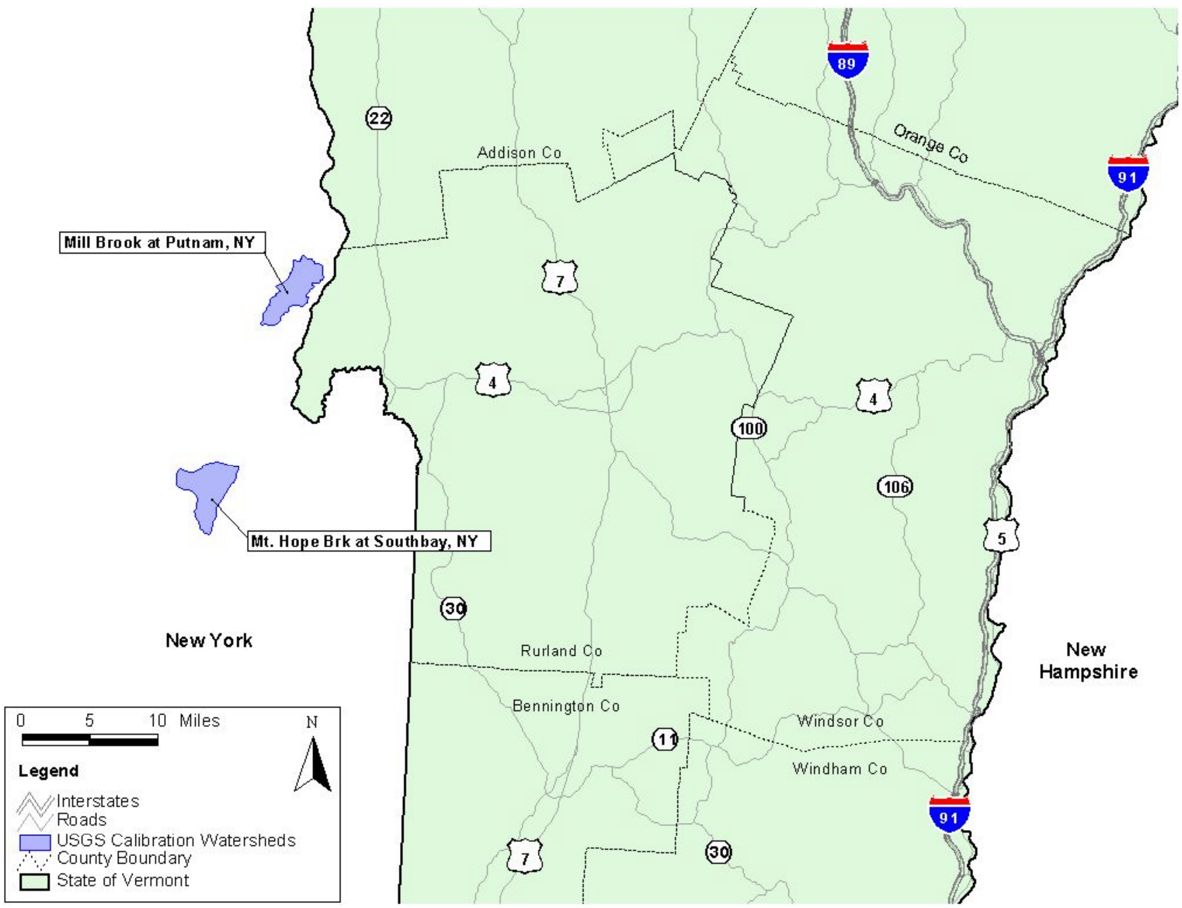


Figure 4.1. Locations of watersheds with USGS gauge data for calibration

Table 4.1. Selected USGS gauged watersheds

	Waterbody	Sq. miles	Gauge No.	PI	CN
1	Mount Hope Brook Southbay near Whitehall, NY	11.6	42791250	1	71
2	Mill Brook Putnam, NY	10.3	427904	2	75

4.1. Mount Hope Brook

Hourly precipitation and daily temperature data (EartInfo Inc., 2003) from Whitehall, NY (NY 9389)-about 5 miles from USGS calibration gauge-were used to simulate the flow from Mount Hope watershed. Model-simulated flow was compared to observed flow at USGS gauge for the calibration process. Among the period when both precipitation and flow data are available, 1993 and 1994 have fewest missing and estimated values. Therefore, the data for 1993 and 1994 were used to calibrate the model.

Initial calibration was targeted to estimate appropriate TC-BF. Model simulated flows for different TC-BF (100, 500, 1000, and 2000 hours) were evaluated to understand the appropriate representation of ground water discharge to the stream. For all these cases, time of concentration for surface runoff (TC-SR) was set a constant of 10 hours assuming that it has little or no influence in variations in daily and larger scale comparisons. Figures 4.2 to 4.5 and 4.7 to 4.10 present the comparison of daily flow and Figures 4.6 and 4.11 present the flow duration curves.

The comparison of simulated daily flow and FDC generated from daily flow at Mount Hope revealed that TC-BF substantially influences the flow simulation. While short TC-BF (100 hours) simulates well the storm-related flow (subsurface interflow), it fails to capture the long-term recession accurately. On the other hand, long TC-BF (2000 hours) captures the long-term recession successfully and fails to simulate the stormrelated flow accurately. Overall, TC-BF of 1000 hours appears the best among the ones considered. The calibration further reveals that the snowmelt was reasonably simulated.

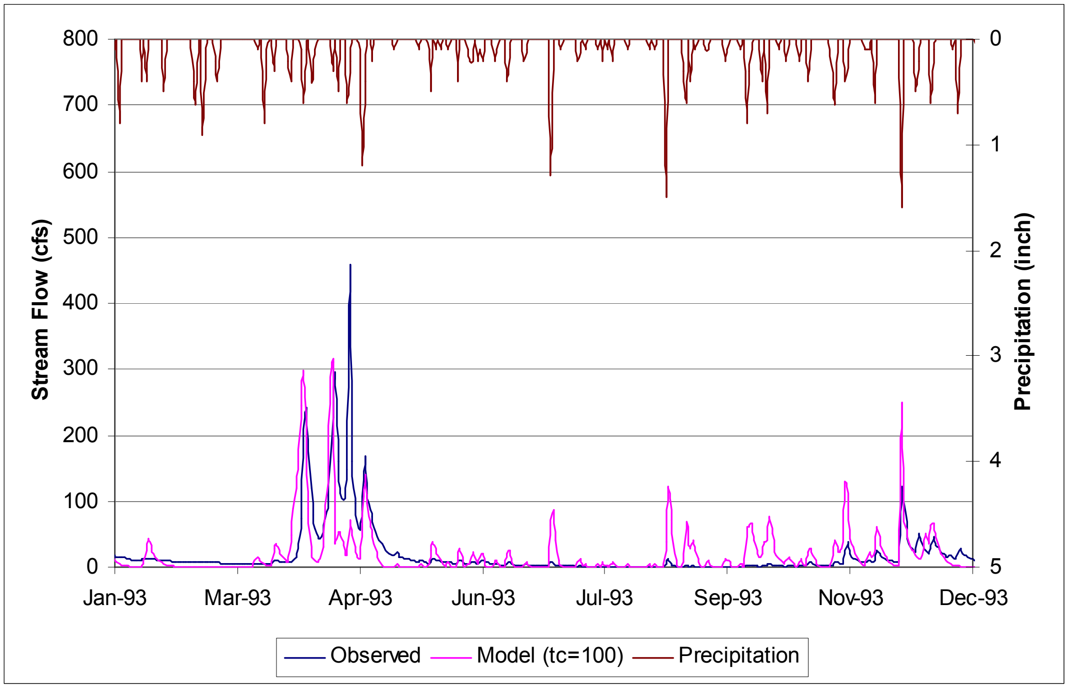


Figure 4.2. Daily flow (TC-BF = 100 hours) at Mount Hope Brook in 1993.

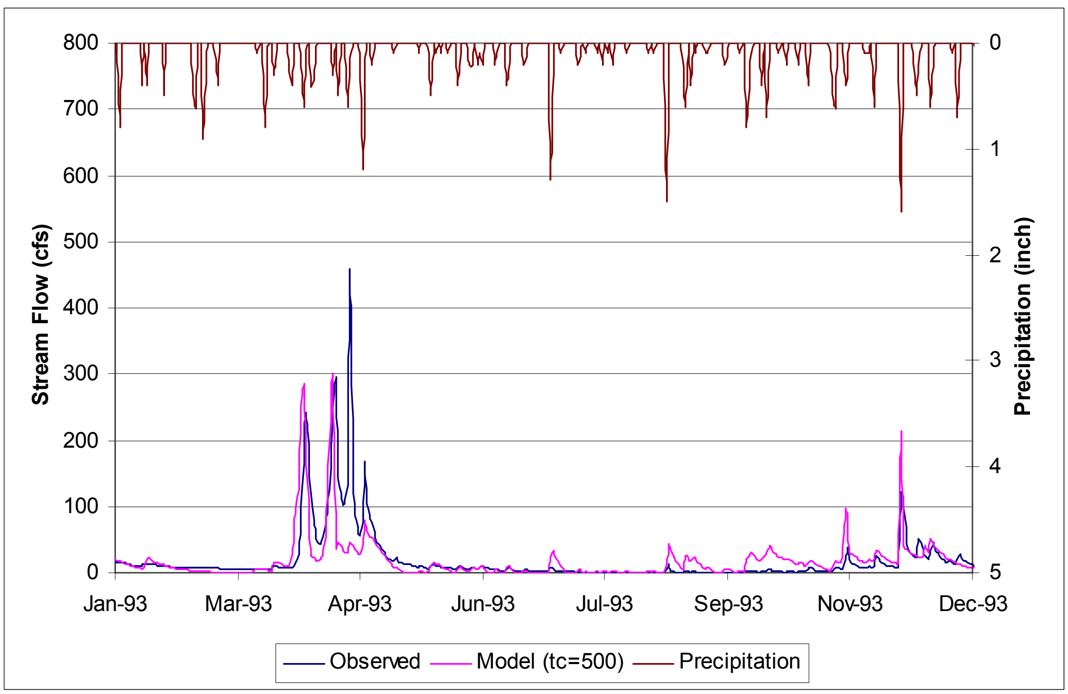


Figure 4.3. Daily flow (TC-BF = 500 hours) at Mount Hope Brook in 1993.

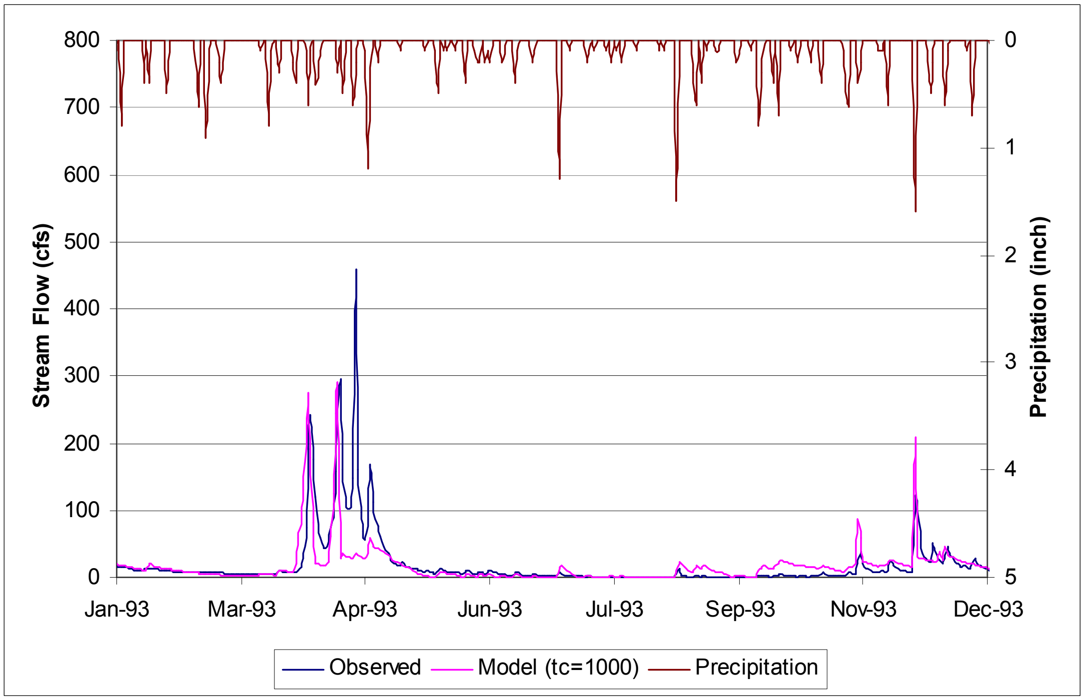


Figure 4.4. Daily flow (TC-BF = 1000 hours) at Mount Hope Brook in 1993.

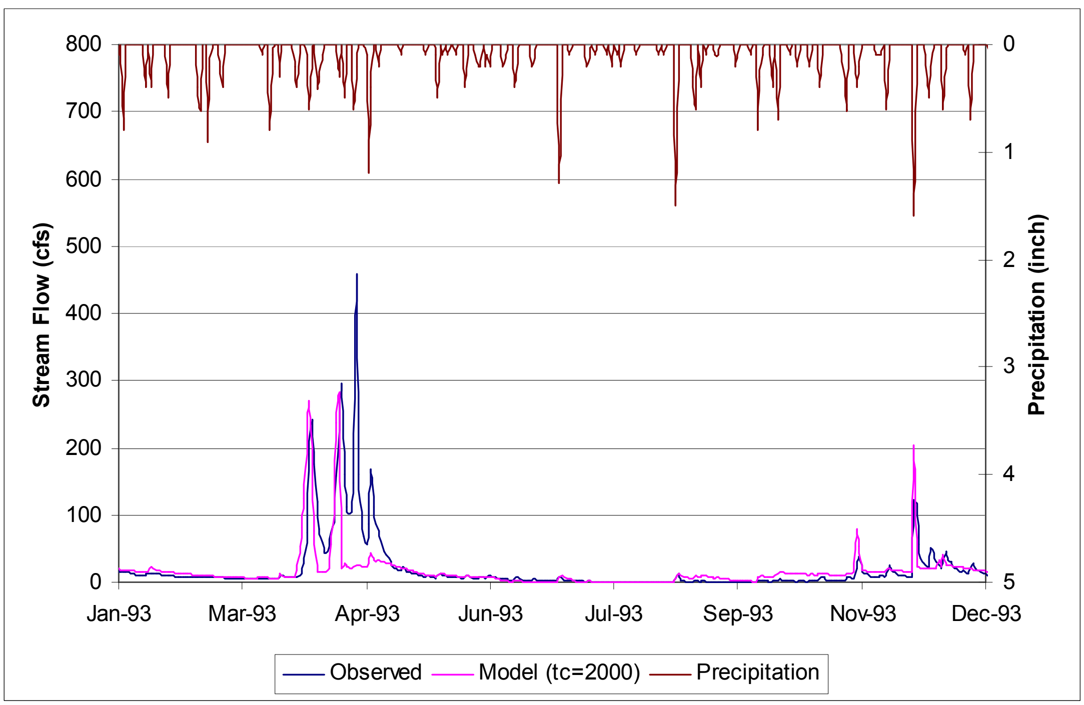


Figure 4.5. Daily flow (TC-BF = 2000 hours) at Mount Hope Brook in 1993.

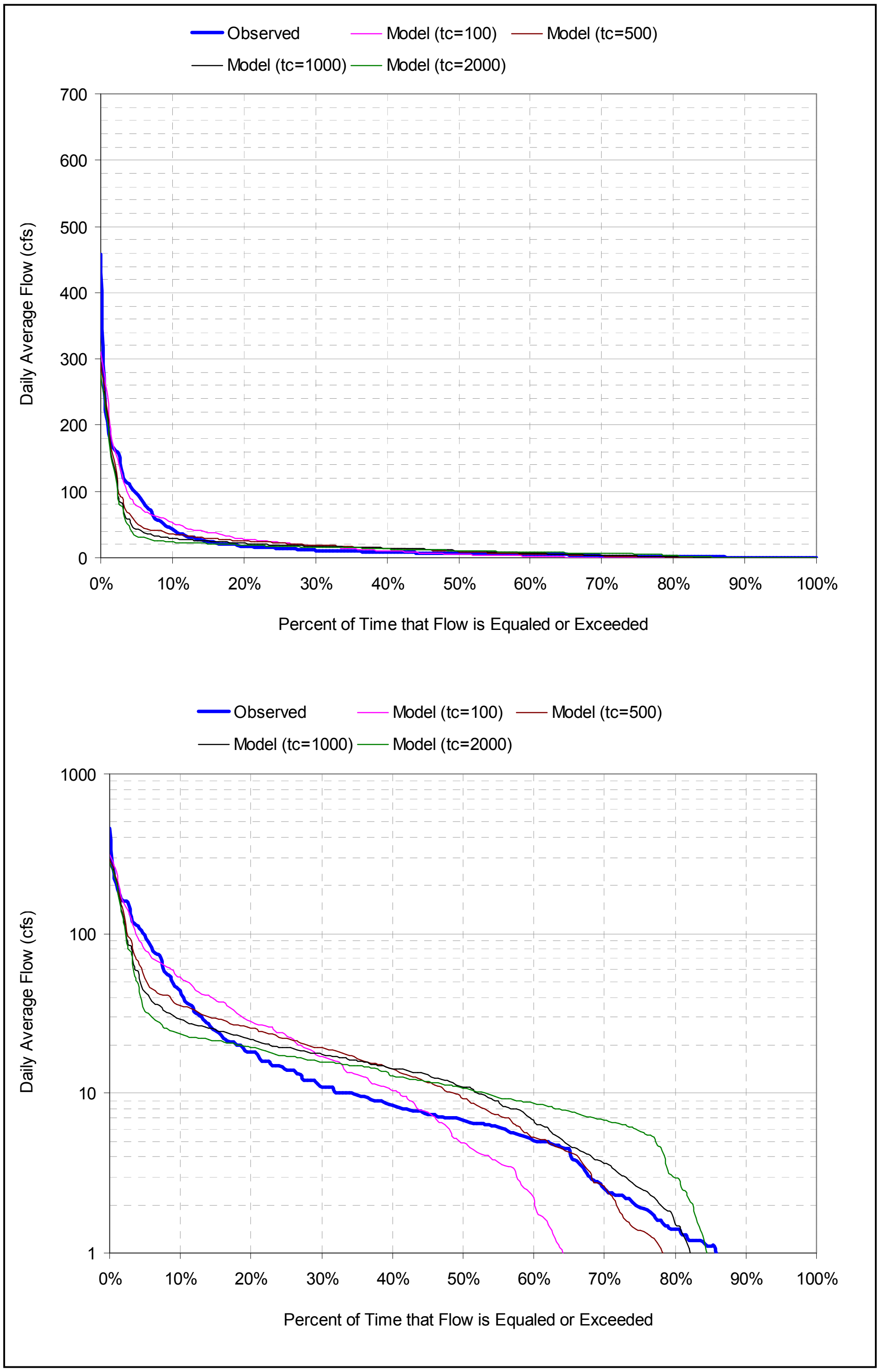


Figure 4.11. Flow duration curve of Mount Hope Brook using 1993 data. Top graph is in normal scale and presents the difference during low-exceedence flow (high flow) clearly. Bottom graph is in log scale and presents the differences during high-exceedence flow (low flow) clearly

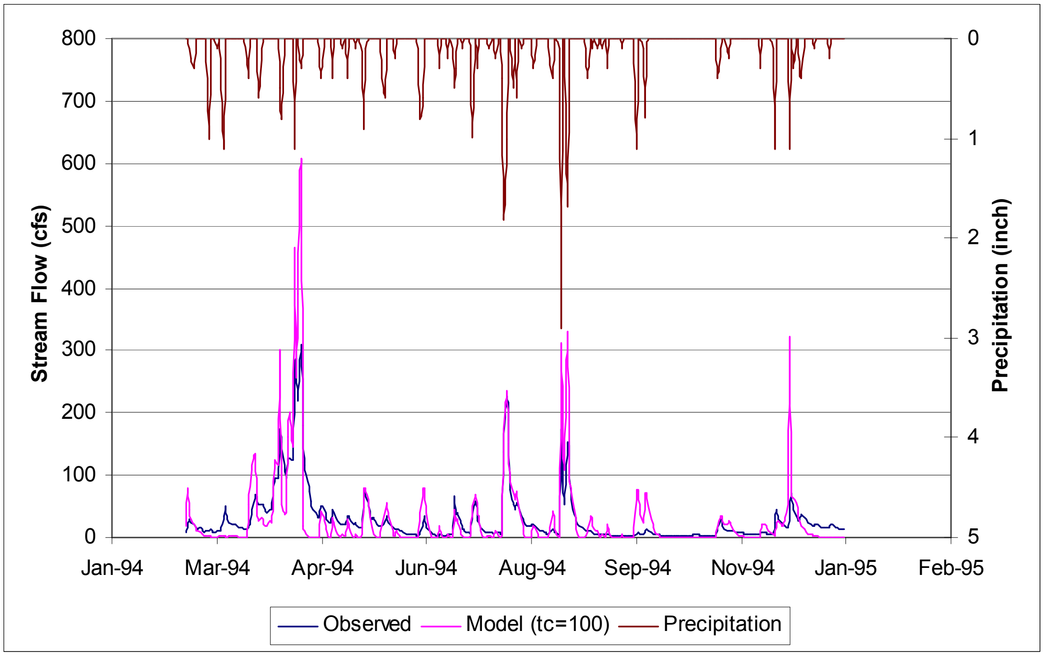


Figure 4.7. Daily flow (TC-BF = 100 hours) at Mount Hope Brook in 1994.

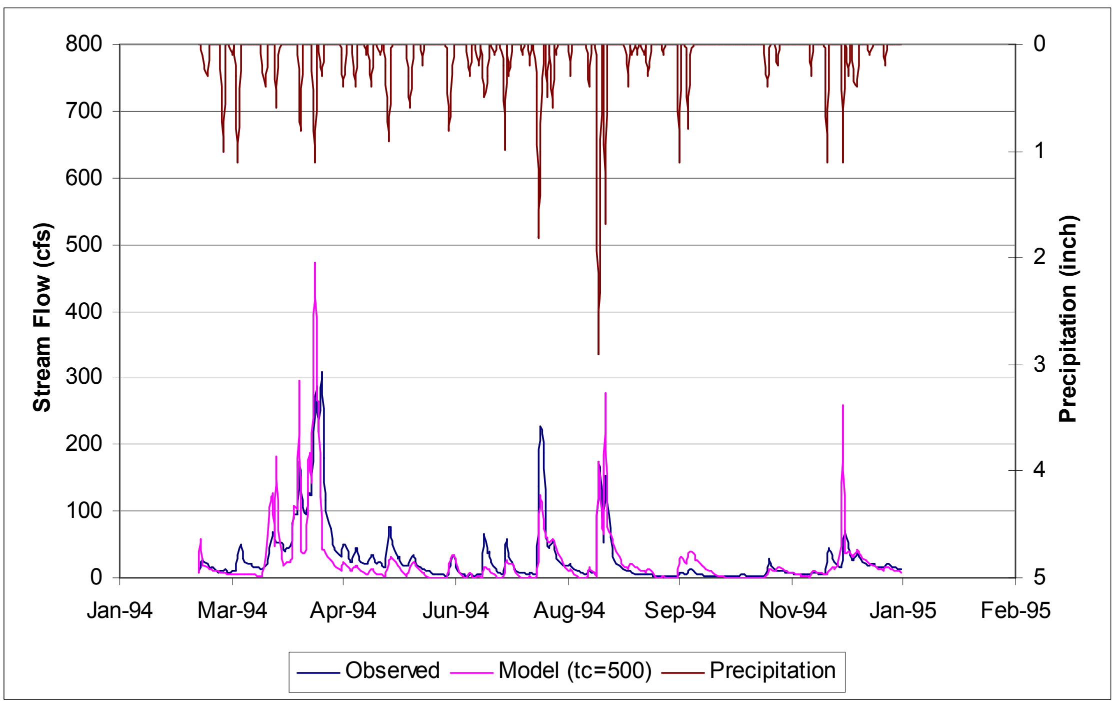


Figure 4.8. Daily flow (TC-BF = 500 hours) at Mount Hope Brook in 1994.

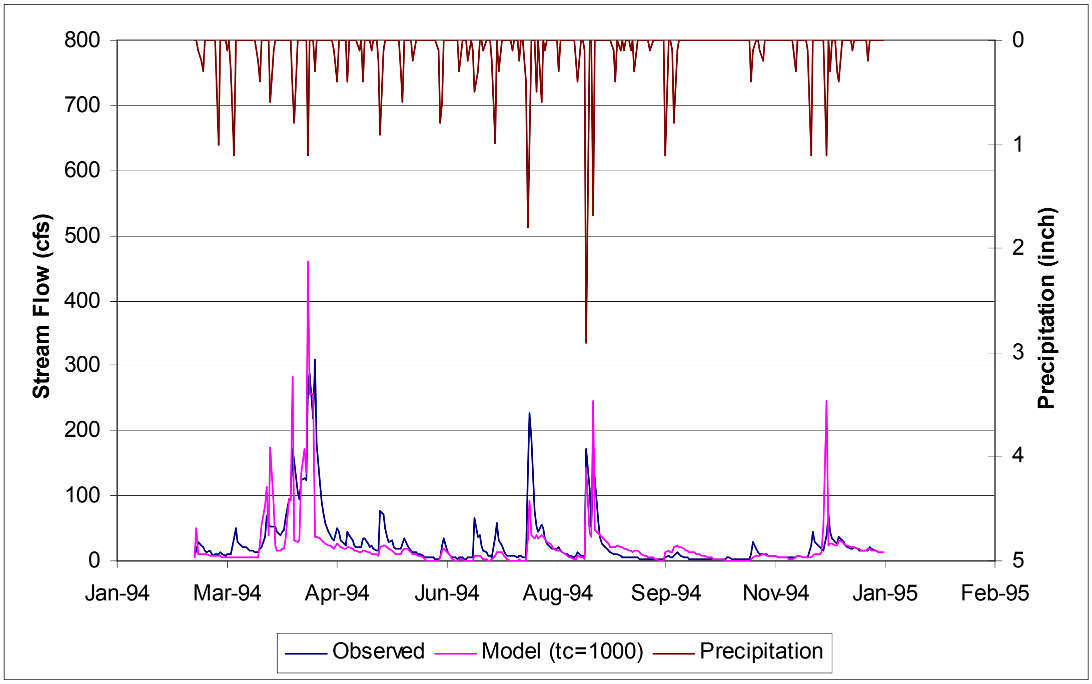


Figure 4.9. Daily flow (TC-BF = 1000 hours) at Mount Hope Brook in 1994.

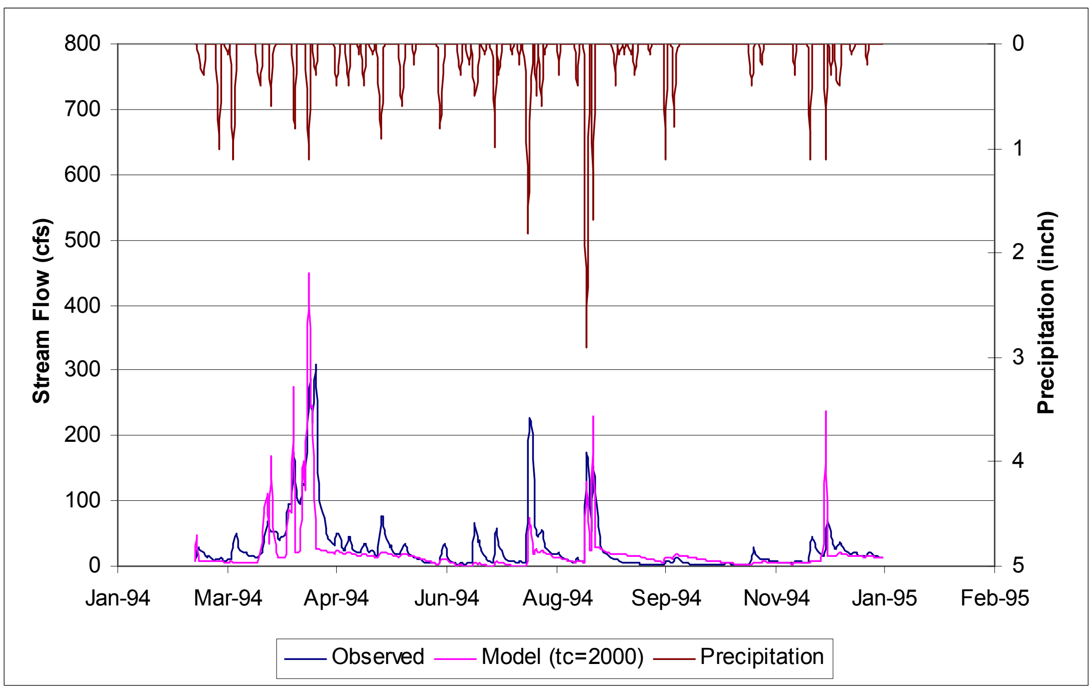


Figure 4.10. Daily flow (TC-BF = 2000 hours) at Mount Hope Brook in 1994.

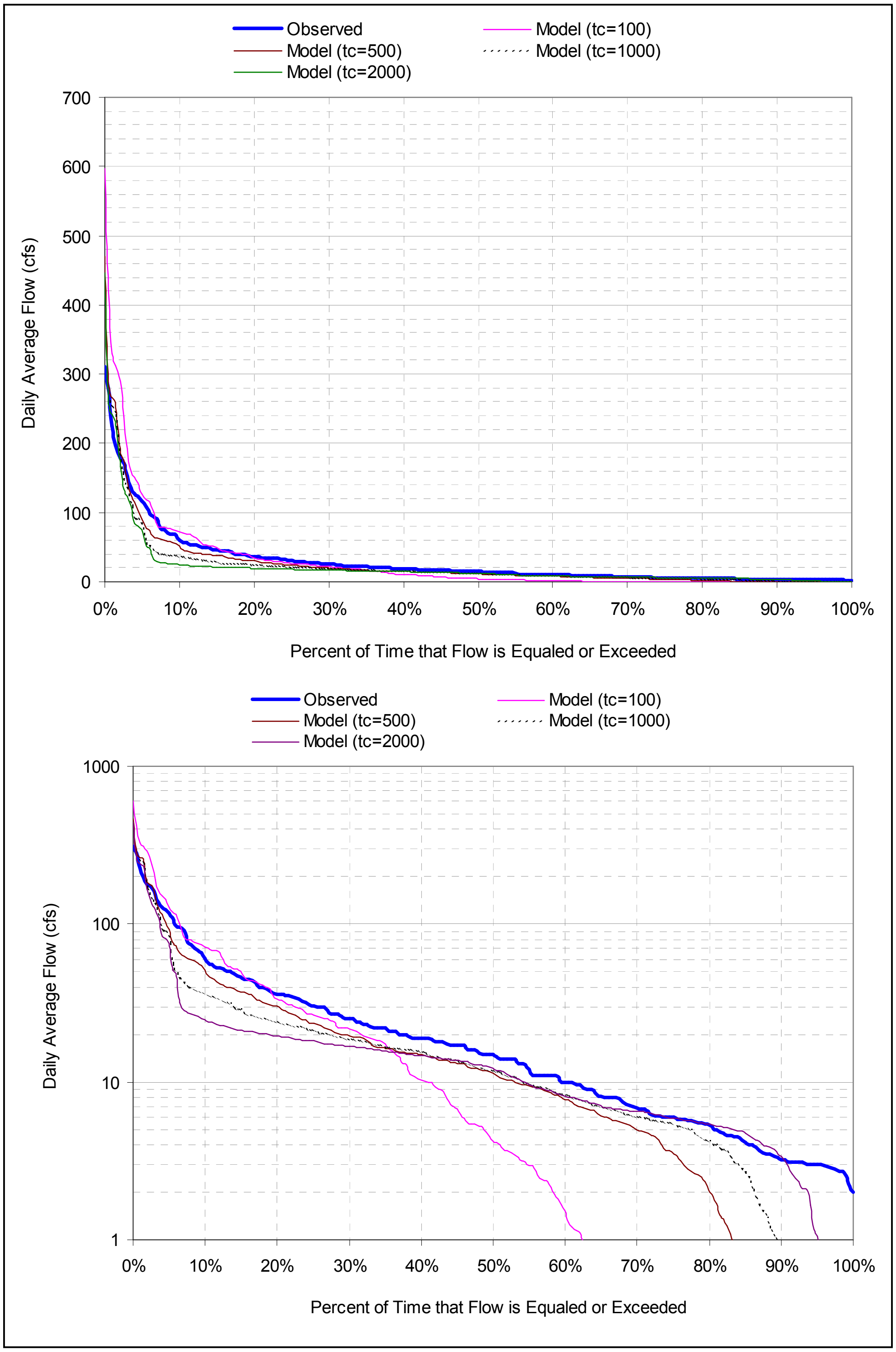


Figure 4.6. Flow duration curve of Mount Hope Brook using 1994 data. Top graph is in normal scale and presents the difference during low-exceedence flow (high flow) clearly. Bottom graph is in log scale and presents the differences during high-exceedence flow (low flow) clearly.

4.2. MILL BROOK

Hourly precipitation data (EarthInfo, Inc., 2003) from Ticonderoga, NY (NY8507 - about 7.5 miles from gauge) and daily temperature data (EarthInfo, Inc., 2003) from Whitehall, NY (NY 9389 - about 13 miles from USGS calibration gauge) were used to simulate the flow from Mill Brook watershed. Model simulated flow was compared to observed flow at USGS gauge for the calibration process. In the period when both precipitation and flow data are available, 1992 and 1993 have few missing and estimated values. Therefore the data for 1992 and 1993 were used to calibrate the model.

Similar to the Mount Hope Brook, the initial calibration for Mill Brook was targeted to estimate appropriate TC-BF. Model-simulated flows for different TC-BF (100, 500, 1000, and 2000 hours) were evaluated to understand the appropriate representation of ground water discharge to the stream. For all these cases, time of concentration for surface runoff (TC-SR) was set a constant of 10 hours assuming that it has little or no influence in variations in daily and larger scale comparisons. Figures 4.12 to 4.15 and 4.17 to 4.20 present the comparison of daily flow and Figure 4.16 and 4.21 present the flow duration curves.

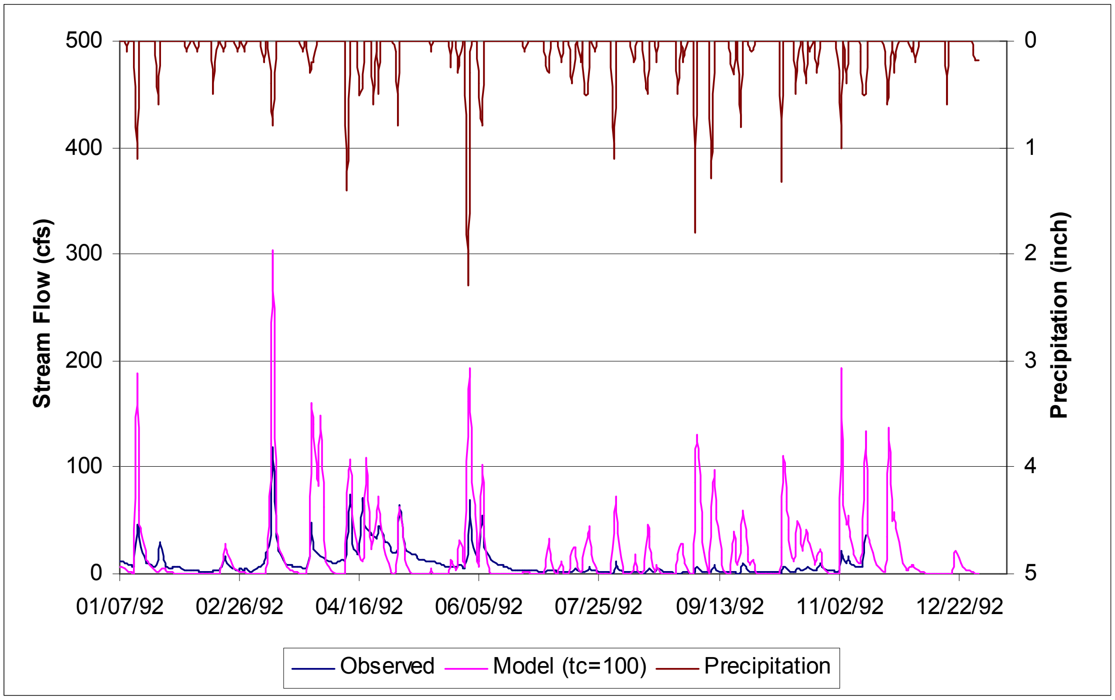


Figure 4.12. Daily flow (TC-BF = 100 hours) at Mill Brook in 1992.

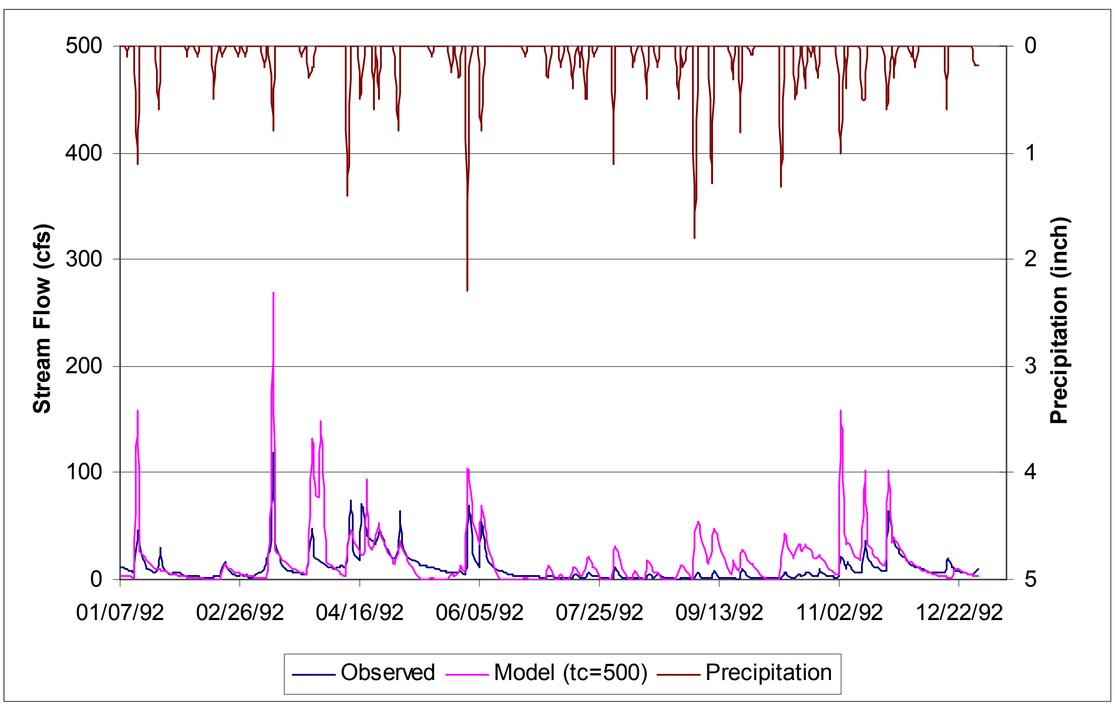


Figure 4.13. Daily flow (TC-BF = 500 hours) at Mill Brook in 1992.

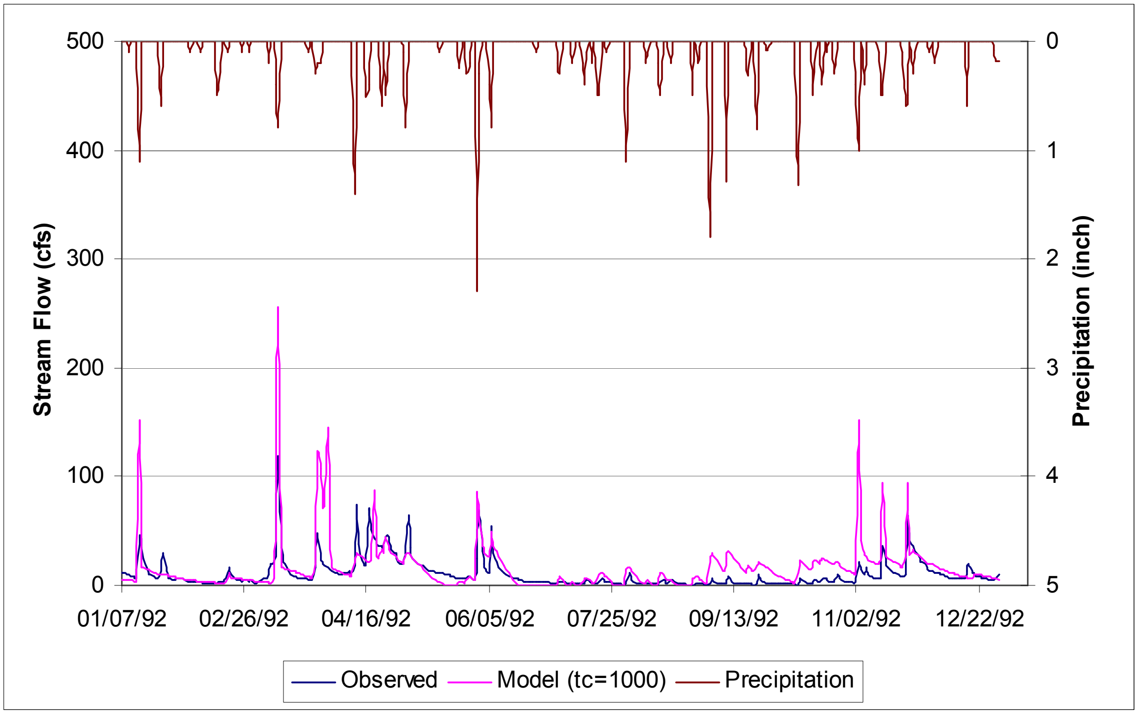


Figure 4.14. Daily flow (TC-BF = 1000 hours) at Mill Brook in 1992.

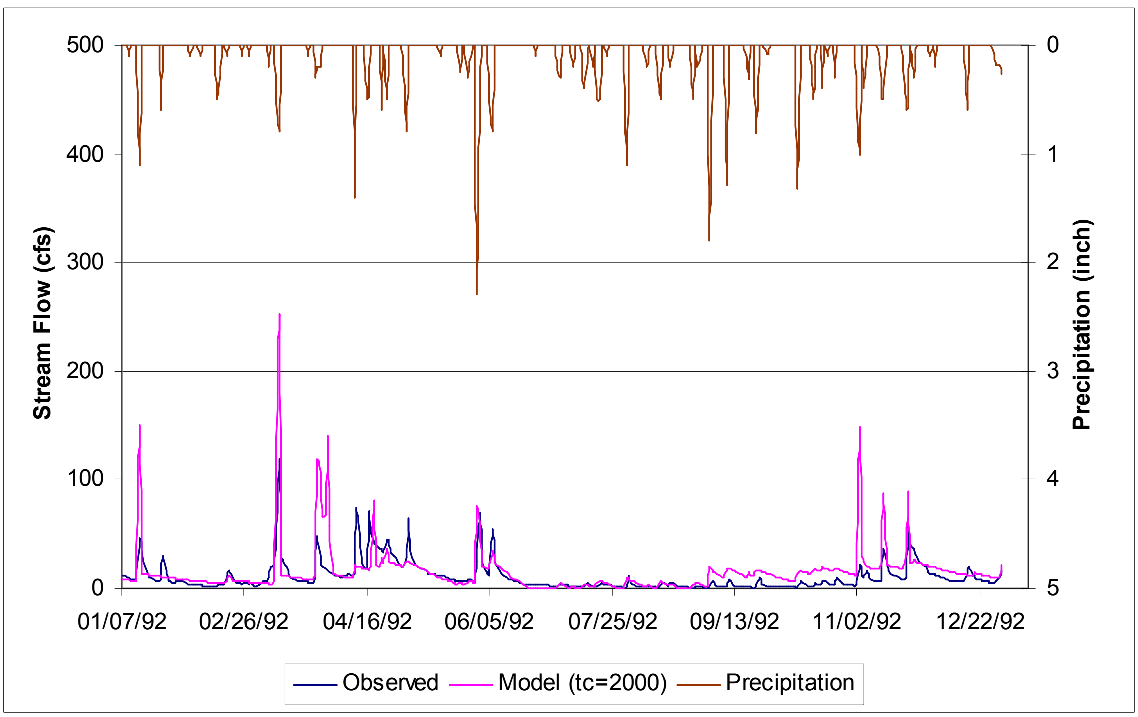
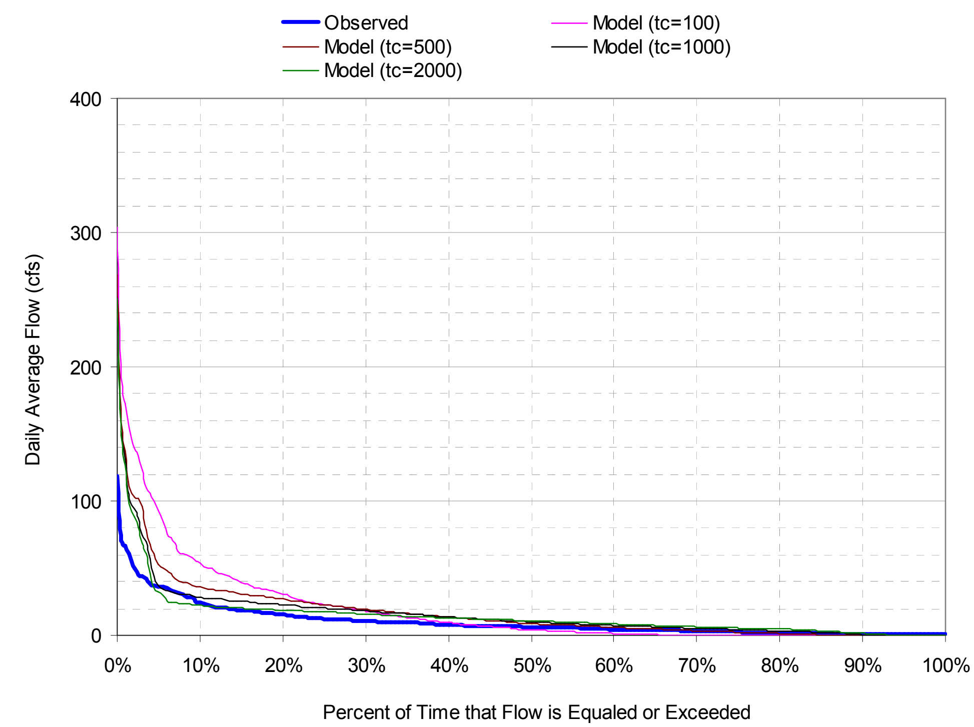


Figure 4.15. Daily flow (TC-BF = 2000 hours) at Mill Brook in 1992.



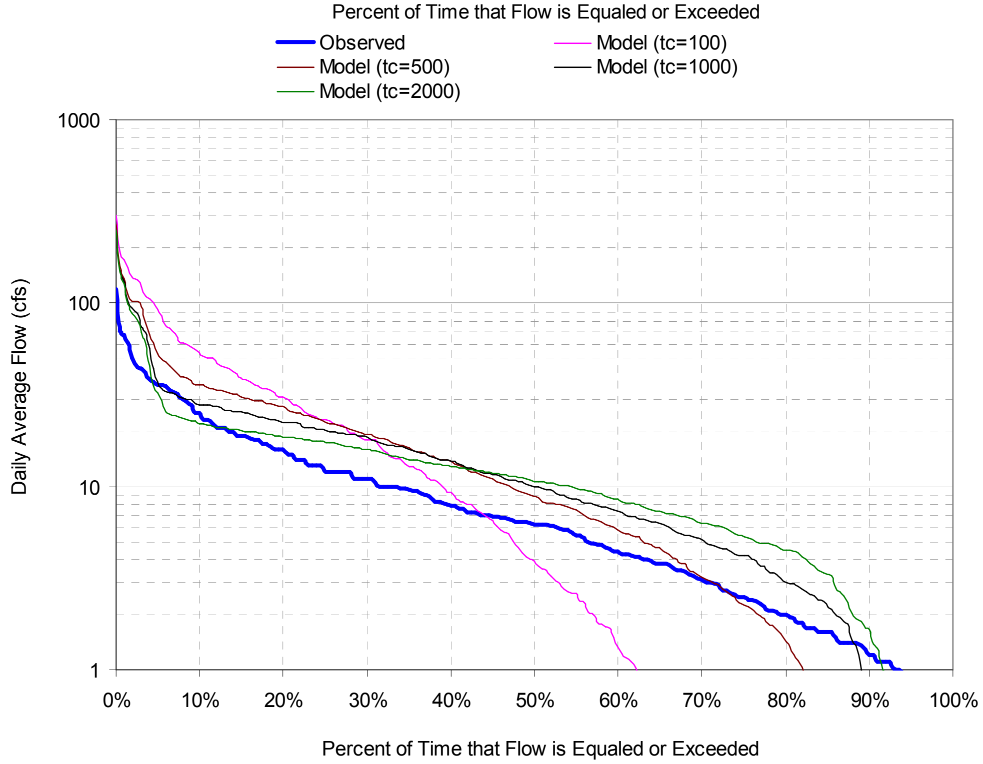


Figure 4.16. Flow Duration Curve of Mill Brook using 1992 data.
Top graph is in normal scale and presents the difference during low-exceedence flow (high flow) clearly. Bottom graph is in log scale and presents the differences during high-exceedence flow (low flow) clearly.

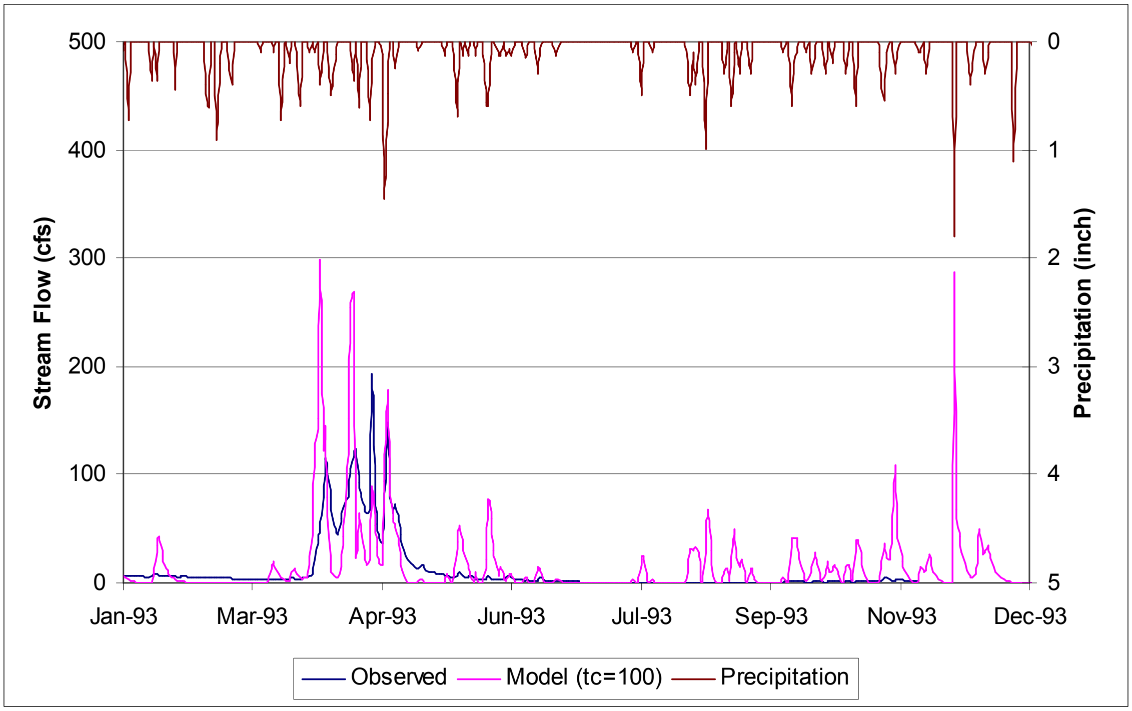


Figure 4.17. Daily flow (TC-BF = 100 hours) at Mill Brook in 1993.

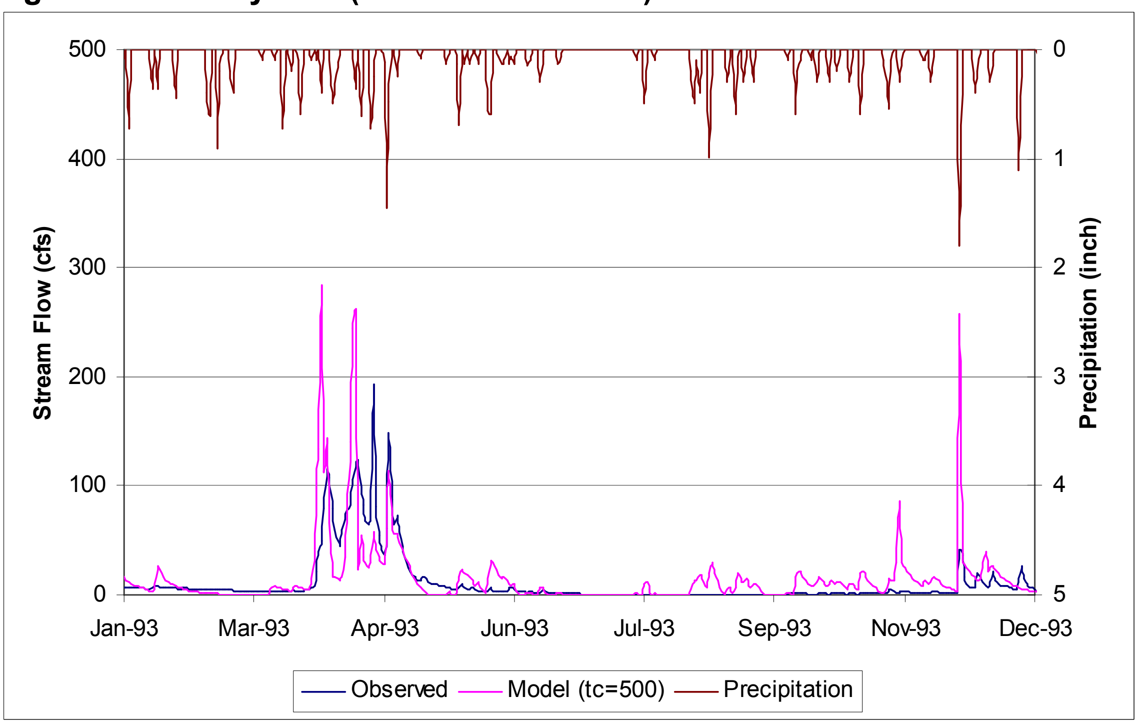


Figure 4.18. Daily flow (TC-BF = 500 hours) at Mill Brook in 1993.

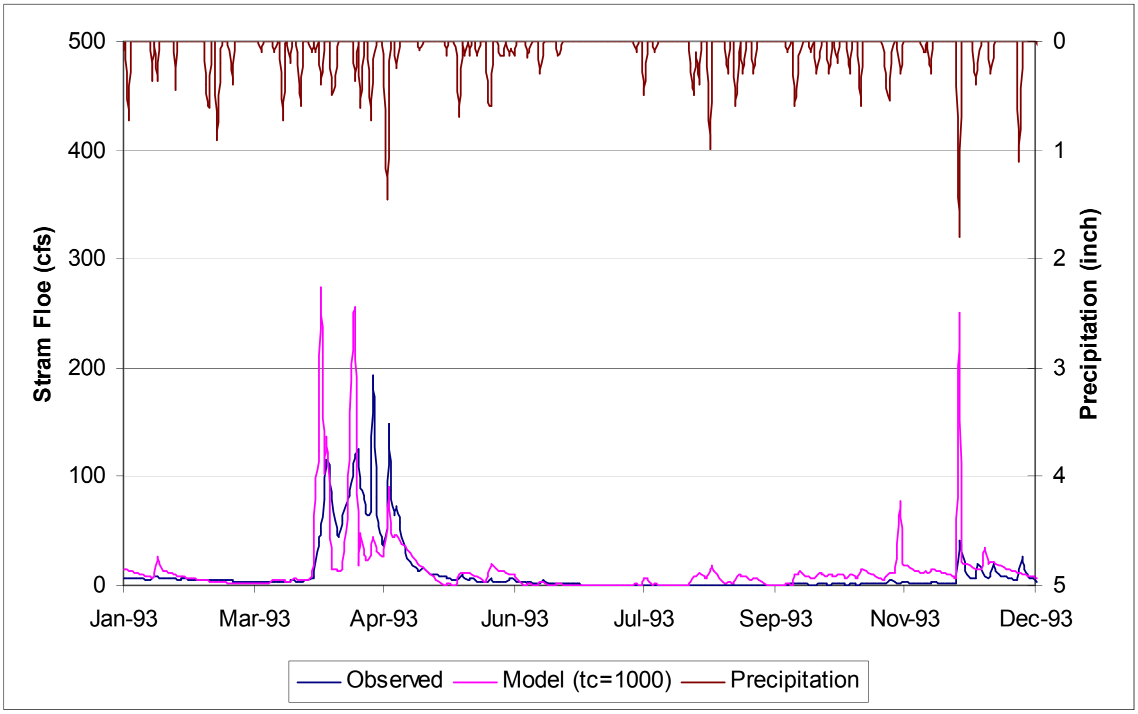


Figure 4.19. Daily flow (TC-BF = 1000 hours) at Mill Brook in 1993.

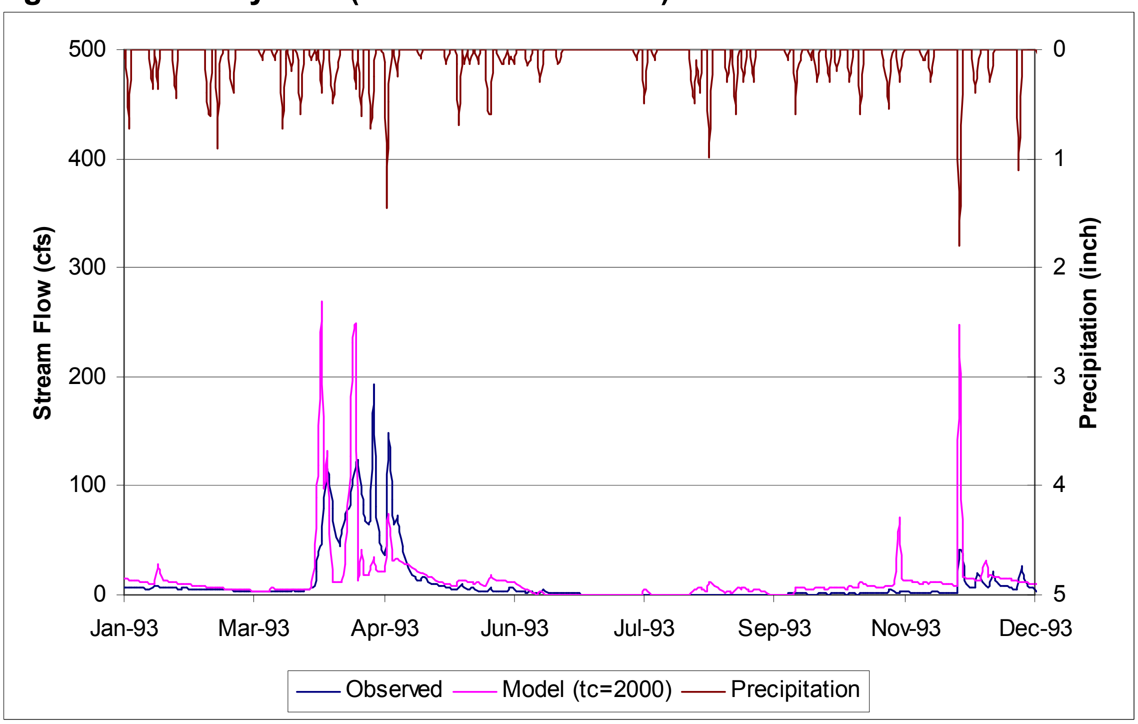


Figure 4.20 . Daily flow (TC-BF = 2000 hours) at Mill Brook in 1993.

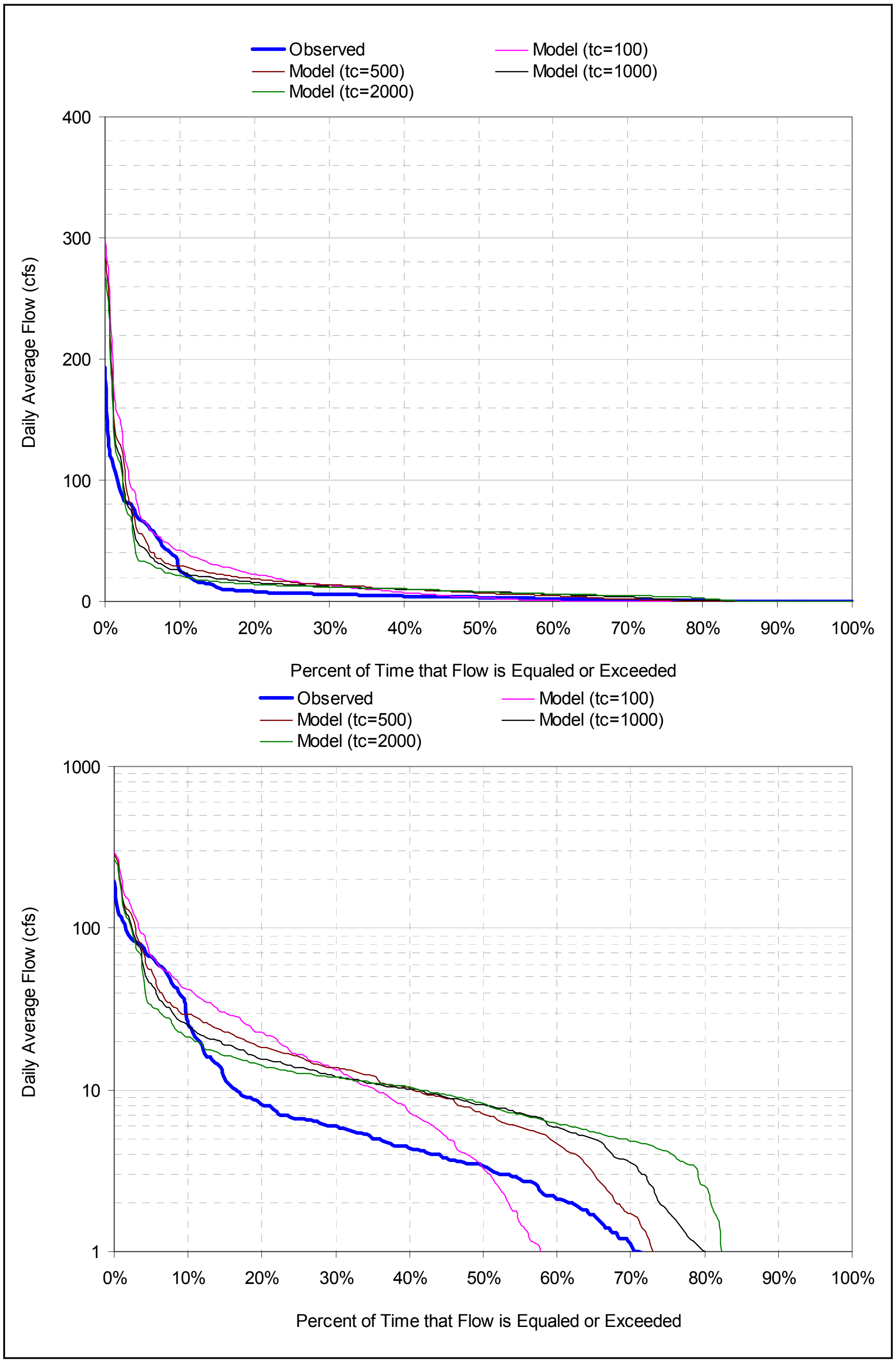


Figure 4.21. Flow Duration Curve of Mill Brook using 1993 data.
Top graph is in normal scale and presents the difference during low-exceedence flow (high flow) clearly. Bottom graph is in log scale and presents the differences during high-exceedence flow (low flow) clearly.

The comparison of simulated daily flow and FDC generated from daily flow at the Mill Brook confirmed the observations made at the Mount Hope Brook that short TC-BF (100 hours) simulates well the storm-related flow (subsurface interflow) and long TC-BF (2000 hours) captures the long-term recession successfully. Similar to the Mount Hope Brook, TC-BF of 1000 hours seems to be the best compromise among the ones considered. The calibration further reveals that the snowmelt was reasonably simulated.

4.3. Summary of Results

Overall, calibration reveals that short TC-BF (100 hours) simulates well the storm-related flow (subsurface interflow) and long TC-BF (2000 hours) captures the long-term recession successfully and TC-BF of 1000 hours seems to be the best compromise. However, the use of a single TC-BF as represented in the present model structure limits the ability of developing and applying FDC. To overcome this limitation, an external ground water enhancement tool was developed and introduced as a post-processor to the existing P8 UCM model structure. The following section presents the details.

Given that the simple representation of snowmelt algorithm and complicated processes involved, the model simulated snowmelt reasonably well. As a result, it was decided to proceed without changes to snowmelt capabilities.

5. GROUND WATER MODEL ENHANCEMENT

In P8 UCM application for a watershed, percolated stormwater is collected and stored in an aquifer device and discharged to the river with a time of concentration (TC-BF). While the water is stored in aquifer, the evaporation is the only process for water loss. As pointed out in the calibration results, using a single TC-BF limits the accuracy of developing FDCs accurately. To improve the ground water simulation using P8 UCM, a tool or post-processor, named "Ground Water Calculator for P8" (Figure 5.1.), was developed. The tool uses simulated percolation from P8 output and estimates base flow reaching the river using the classic simple approach, "Linear Reservoir Ground water model" following Haan (1972). In this lumped parameter approach, the soil was divided into unsaturated, shallow saturated, and deep saturated zones (Figure 5.2). The shallow saturated zone is modeled as a simple linear reservoir.

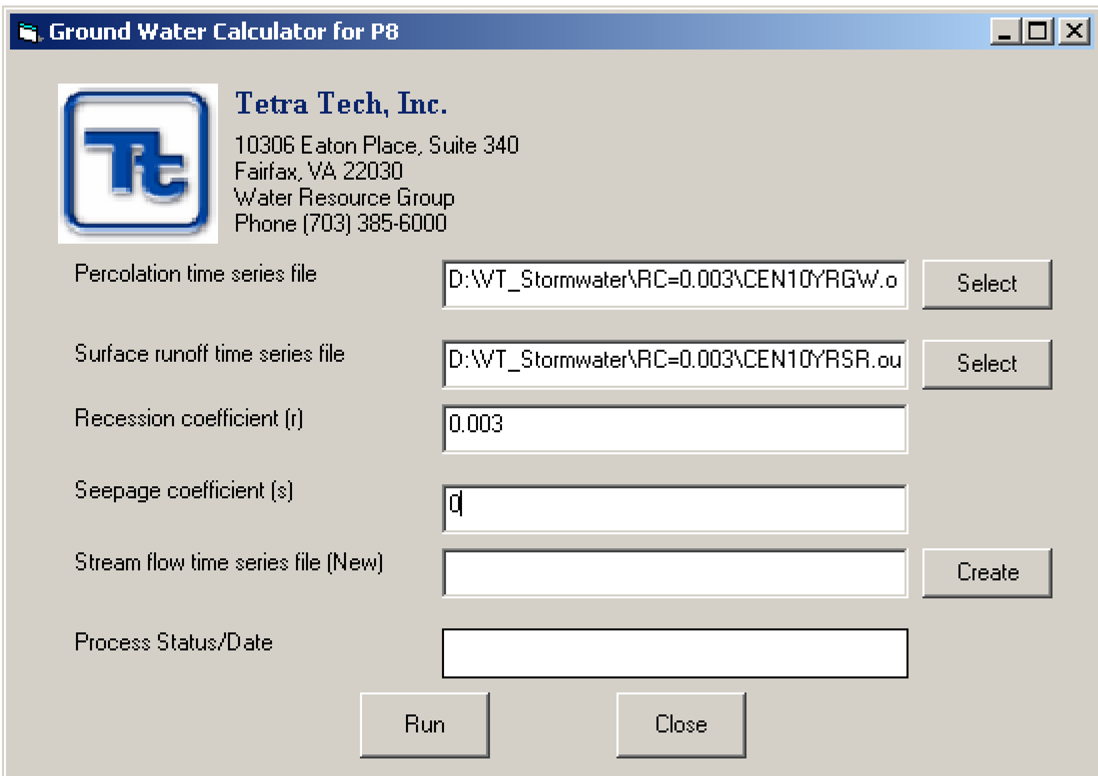


Figure 5.1. Ground Water Calculator, a tool developed to improve P8 UCM model.

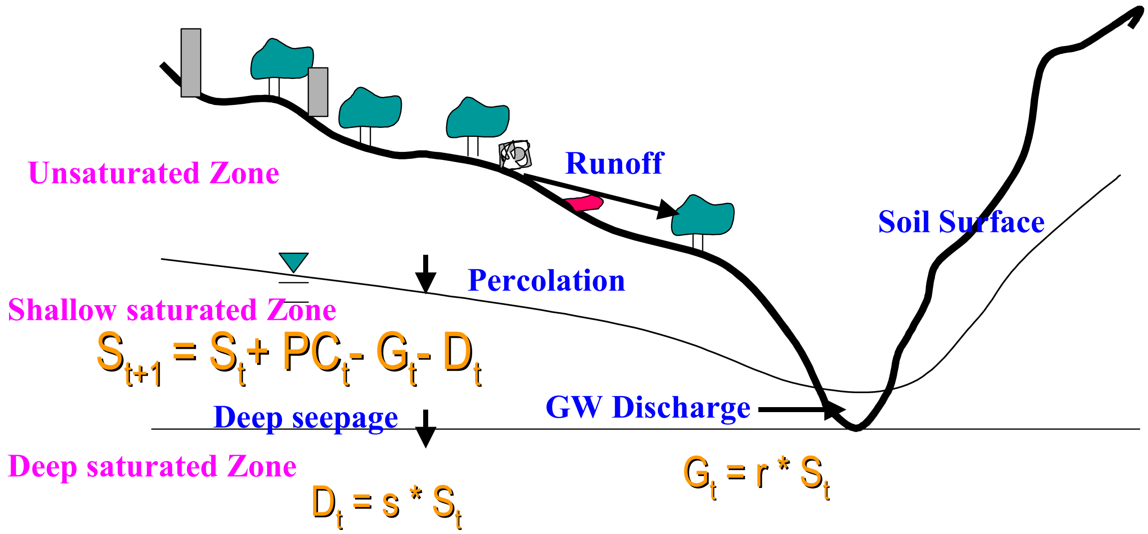


Figure 5. 2. Soil zones as presented by Haan (1972) and Haith et al., (1992).

Ground water reaching the stream (base flow) $G_t = r * S_t$
Deep Seepage or other ground water losses $D_t = s * S_t$

S_t – Storage in the shallow saturated zone at time t
r – Recession Coefficient
s – Seepage or Loss Coefficient

In summary, the approach yields a large volume of water to streams during or after storm events and yields a low volume of water during recession events based on the storage of water in shallow saturated zone. The same approach is used in the widely applied Generalized Watershed Loading Functions (GWLF) model (Haith et al., 1992).

The input and out put parameters of the tools are as follows.

Tool Input

PC_t – Time Series Percolation from P8 (P8 output file)
R_t – Time Series Surface Runoff from P8 (P8 output file)
r – Recession Coefficient
s – Seepage or Loss Coefficient

Tool Processing

$S_{t+1} = S_t + PC_t - G_t - D_t$

S_t – Storage at time t
PC_t – Percolation at time t
G_t – Ground water reaching the stream (base flow)
D_t – Deep Seepage or other ground water losses

$G_t = r * S_t$
$D_t = s * S_t$

$F_t = R_t + G_t$

Tool Output

Ft – Time Series Stream Flow

The tool was tested using hourly flow observations of University of Vermont (UVM) gauges in and around Burlington. The details of UVM watersheds are presented in the next section. The following graphs (Figures 5.3 through 5.6) present the comparison of observed and modeled flow after adding the ground water calculator for P8 UCM model.

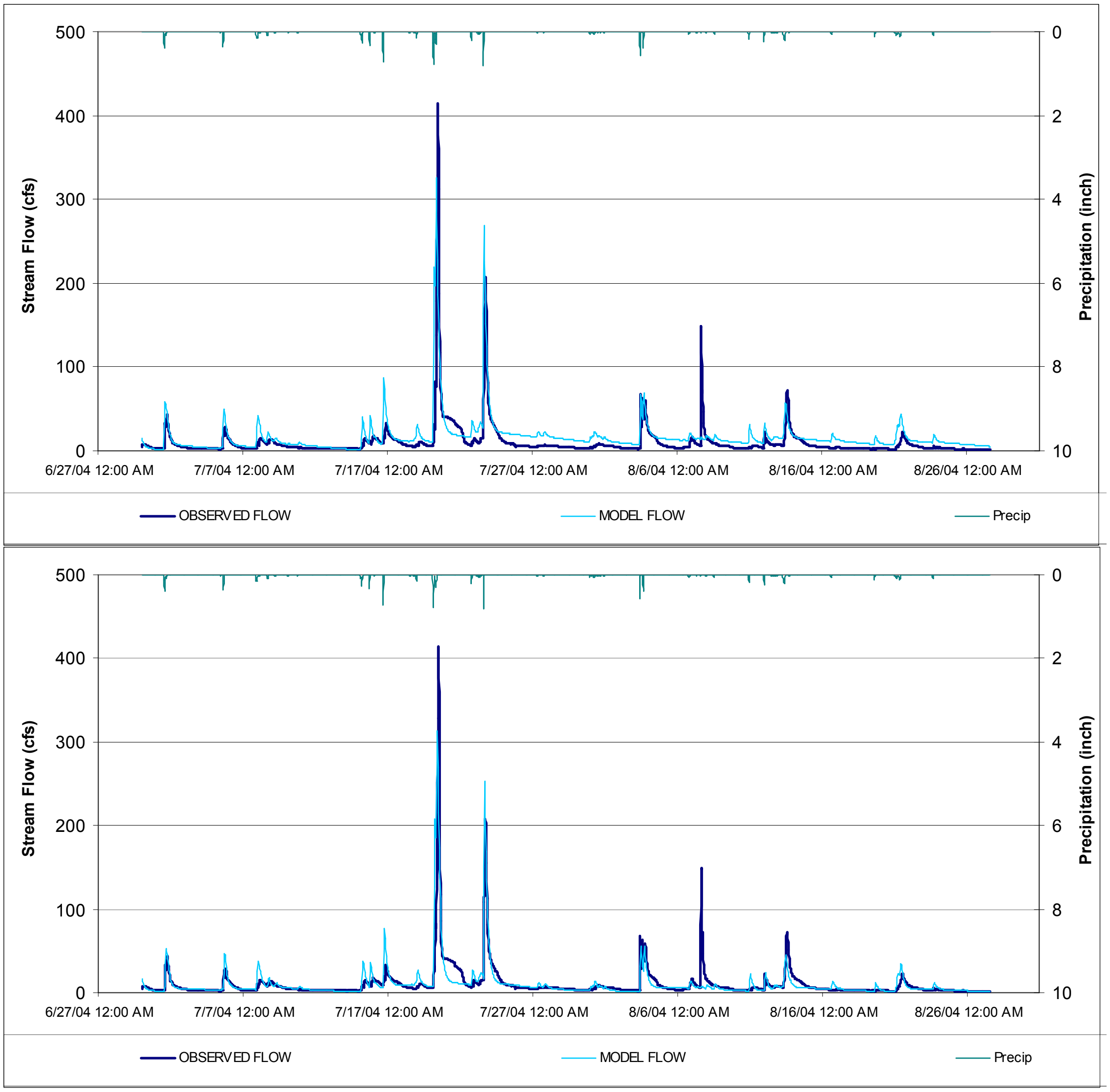


Figure 5.3. Modeled and observed flow before (top) and after (bottom) ground water modification at Potash Brook.

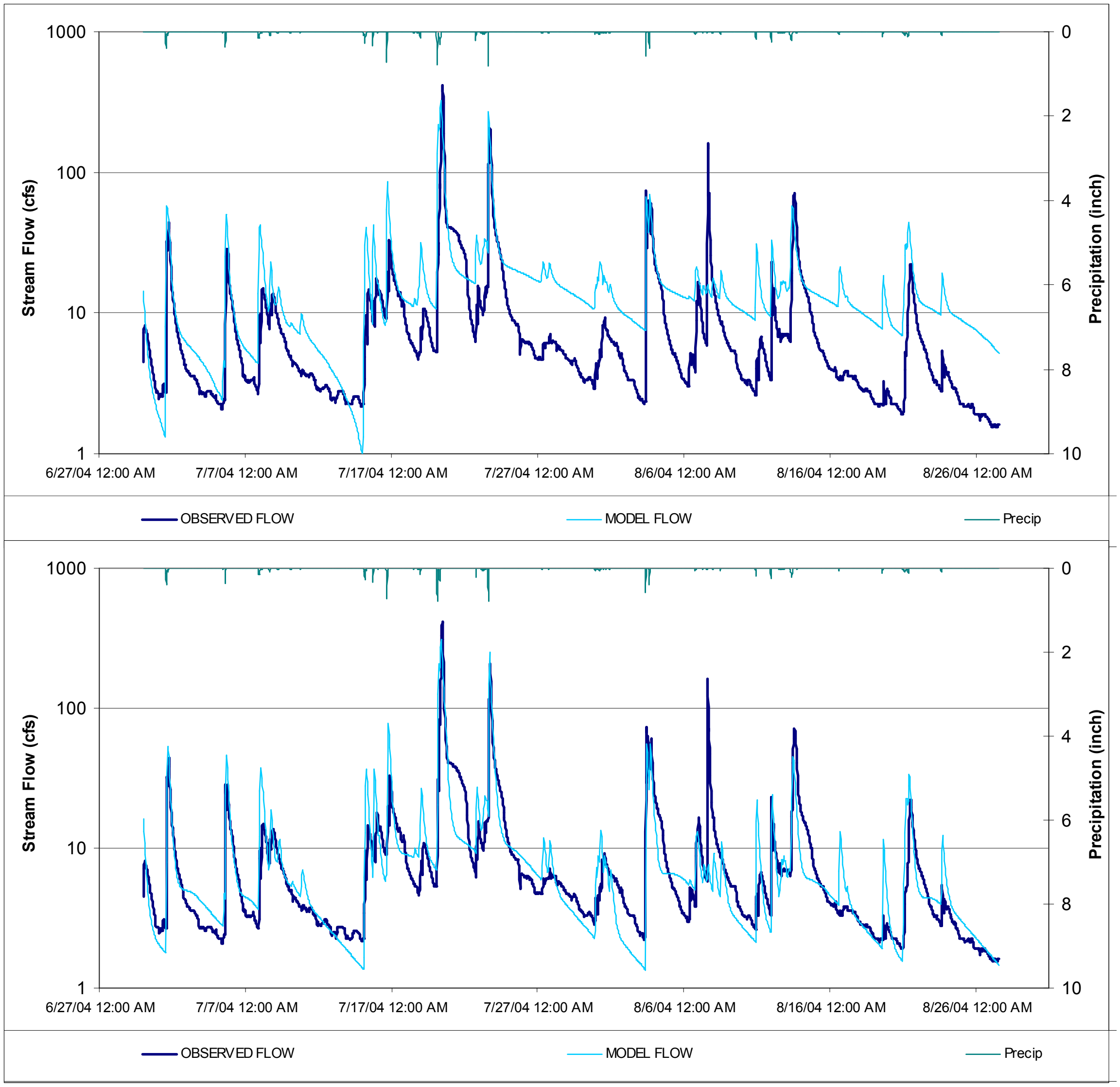


Figure 5.4. Modeled and observed flow before (top) and after (bottom) ground water modification in log scale at Potash Brook.

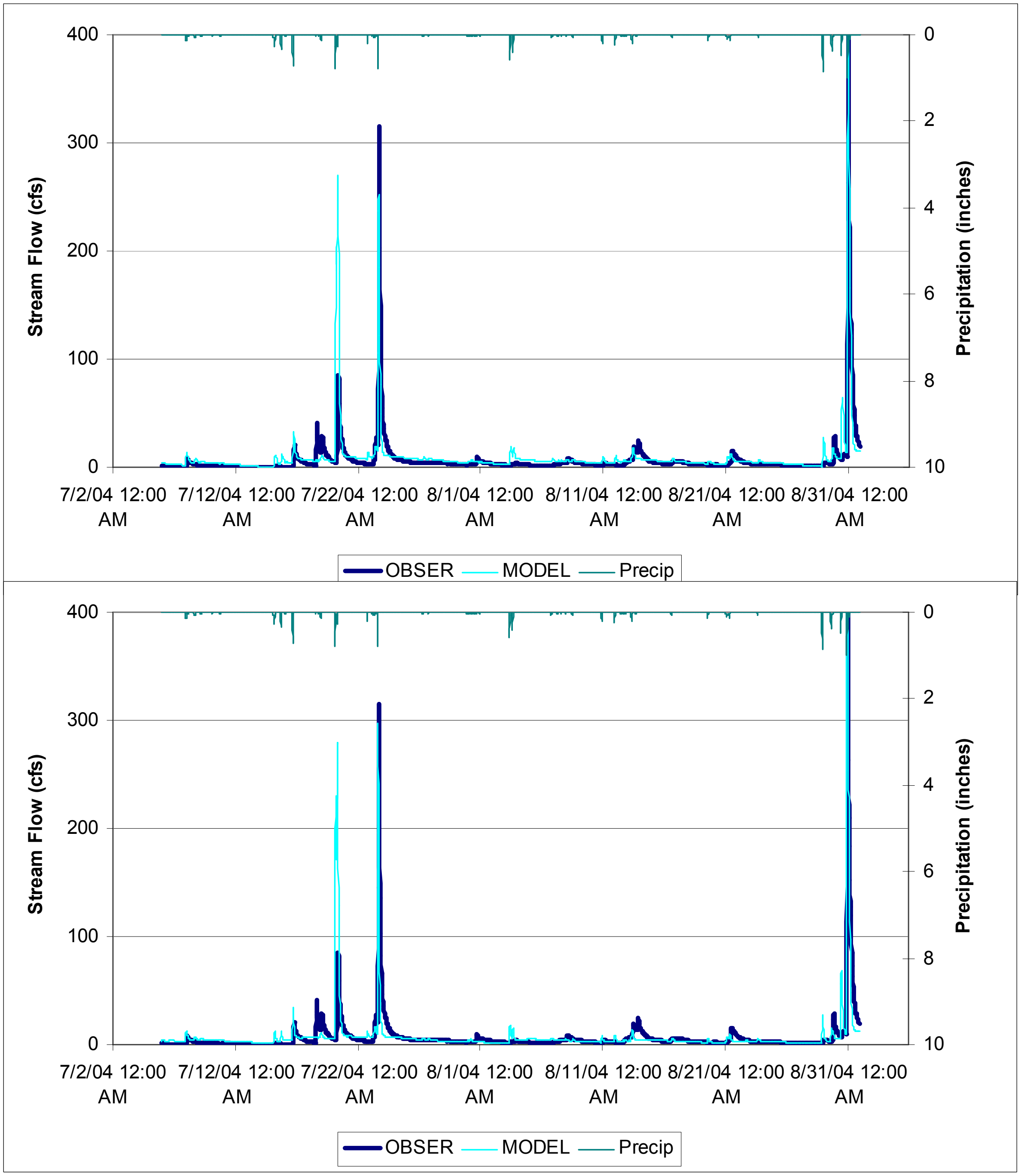


Figure 5.5. Modeled and observed flow before (top) and after (bottom) ground water modification at Jonnie Brook.

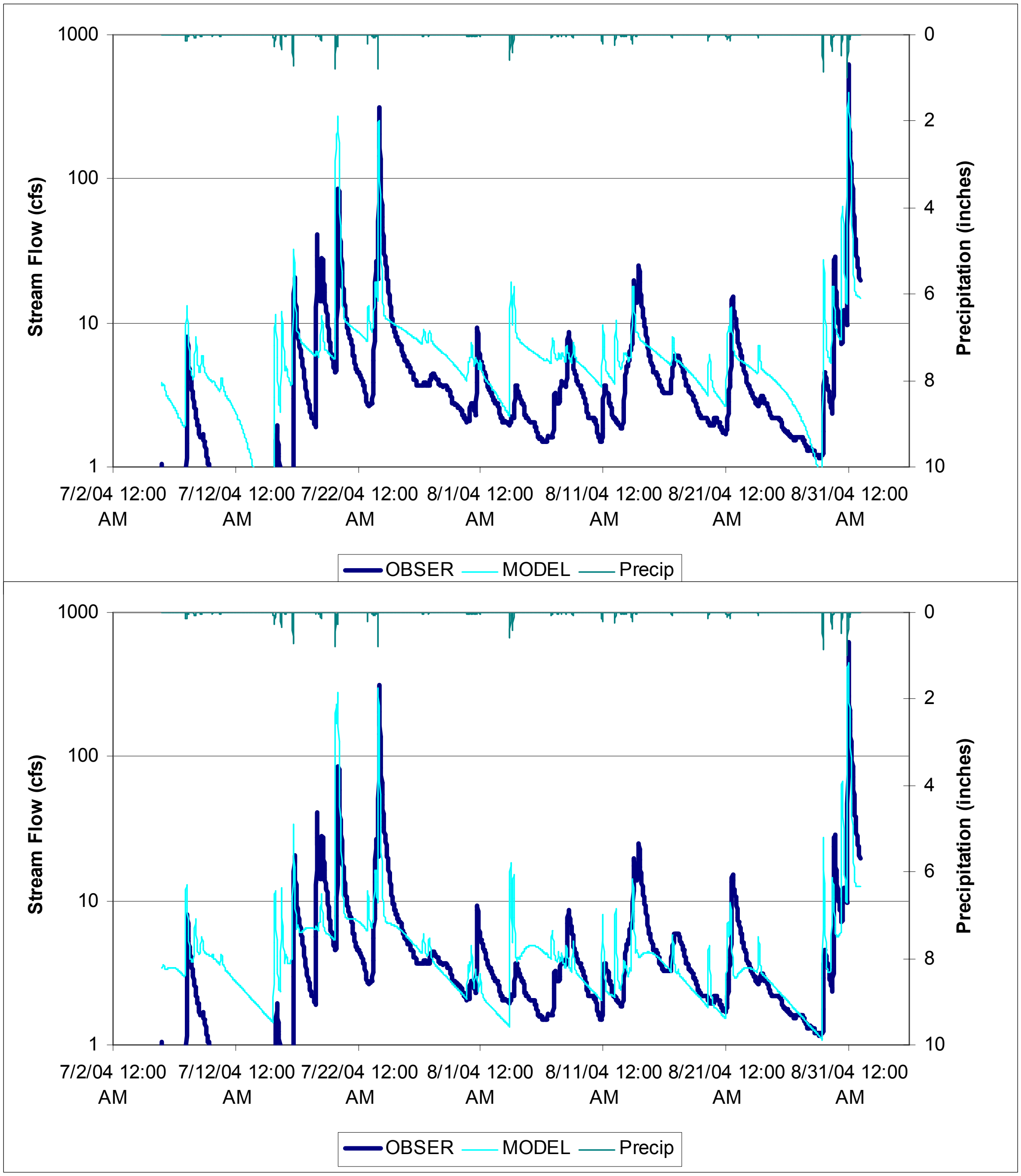


Figure 5.6. Modeled and observed flow before (top) and after (bottom) ground water modification in log scale at Jonnie Brook.

6. CALIBRATION WITH HOURLY FLOW DATA

UVM collected flow measurements at 15-minute intervals during the summer of 2004 at six locations (Figure 6.1). Tables 6.1 and 6.2 Provide details associated with each gauge. For comparison to the P8 UCM model's hourly predictions, the 15-minute flow measurements were aggregated to hourly values. With a specific focus on stormwater and its impacts in small watersheds, the study team decided to make use of the hourly flow data collected by UVM for detailed calibration of model parameters. This section presents the details of calibration.

The objective of this detailed calibration process is to confirm that the application of P8 UCM model and ground water enhancement are appropriate. It also tests and validates the procedures of estimating input parameters so that the model can be successfully applied to develop time-series flow and flow duration curve for ungauged impaired and attainment watersheds with reasonable assurance.

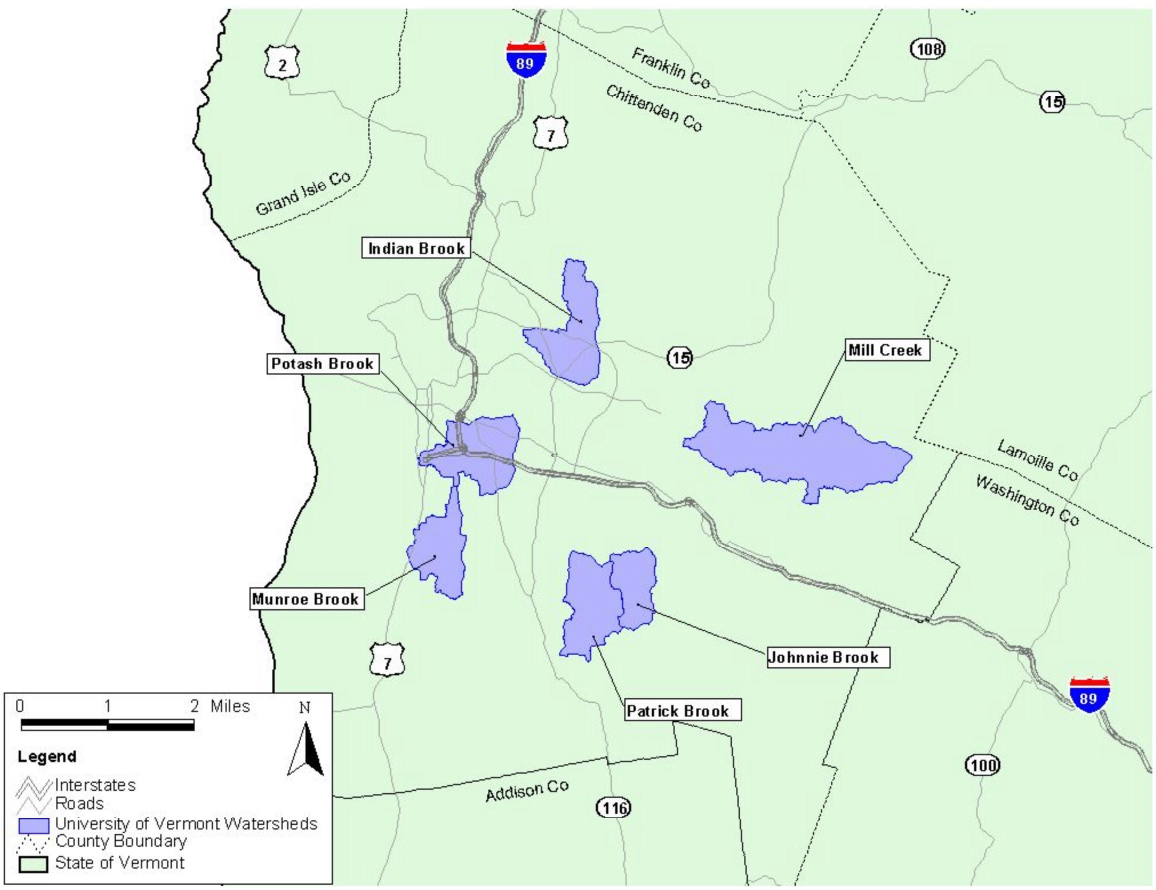


Figure 6.1. The locations of watersheds where UVM gauges are installed.

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Table 6.1. Drainage characteristics for UVM gages: land use and soil

	Watersheds	Total area (acres)	Land use (% by area)								Hydrology group (% by area)			
			Residential	Commercial	Industrial	Transportation	Other urban	Forest	Wetland/water	Agri. related	A	B	C	D
1	Johnnie	2517	5%	0%	0%	3%	0%	76%	5%	11%	2%	1%	46%	52%
2	Potash	4587	21%	10%	1%	19%	3%	10%	7%	29%	29%	10%	18%	43%
3	Indian	4476	17%	3%	0%	11%	11%	32%	7%	19%	15%	7%	17%	60%
4	Mill	10275	4%	0%	0%	4%	1%	73%	8%	10%	16%	6%	41%	37%
5	Munroe	3373	16%	2%	1%	6%	3%	26%	38%	8%	5%	11%	18%	66%
6	Patrick	4114	19%	0%	0%	6%	0%	46%	12%	17%	11%	1%	33%	55%

Table 6.2. Drainage characteristics of UVM gauges: percent imperviousness, SCS curve number, and average slope

	Watersheds	Total area (Acres)	Percent imperviousness	Pervious curve number	Average slope
1	Johnnie	2517	2	76	14%
2	Potash	4587	22	69	5%
3	Indian	4476	16	73	7%
4	Mill	10275	3	70	18%
5	Munroe	3373	9	77	6%
6	Patrick	4114	6	74	11%

6.1. Model Parameters and Estimation

Inputs to P8 UCM for hydrologic simulation include climatological data, percent imperviousness (PI), pervious curve number (PCN), and times of concentration for ground water base flow (TC-BF) and surface runoff (TC-SR). This section details the estimation of these parameters.

6.1.1. Climatological Data

Hourly time-series data for the Burlington International Airport, Burlington, VT station were downloaded from the National Oceanic and Atmospheric Administration (NOAA) and the National Climatic Data Center (NCDC) Unedited Local Climatological Data (ULCD) system for Oct. 2003–Sep. 2004. The data include hourly precipitation and temperature, which are the major climate inputs for P8 UCM. As all the gauges were within the 10-mile radius of the Burlington Airport, the same weather data were used in all UVM gauged watersheds.

6.1.2. Percent Imperviousness and Impervious Coefficient

PI was estimated (Table 6.2) using a previously developed relationship (CWP et al., 1999) for the VCGI land use data layer as described in section 3. IC was estimated through model calibration.

6.1.3. Pervious Curve Number

P8 UCM uses the curve number (CN) approach for hydrologic simulation of pervious areas. As such, weighted CNs for the pervious portions of each modeled watershed were estimated (Table 6.2) using VCGI land use and detailed SSURGO soils data as described in Section 3.

6.1.4. Time of Concentration for Surface Runoff (TC-SR)

TC-SR is the same as the traditional definition of hydrological time of concentration, i.e., the time runoff takes to travel from the farthest point in the watershed to the watershed outlet. It was revealed during the comparison of model simulations with hourly flow observations at the UVM gauges that TC-SR was a sensitive model parameter, especially in the hourly flow estimations. Therefore, it was considered one of the calibration parameters. The detailed evaluation of TC-SR is presented in the following sections.

6.2. Model Calibration

Among the six UVM watersheds, Potash, Indian, and Munroe Brooks are impaired watersheds. Patrick Brook was excluded in the calibration process because it includes large water impoundments such as lakes, ponds, and wetlands that are believed to strongly affect stream flow responses to rainfall events.

Each watershed was represented in P8 UCM using a simple framework as portrayed in Figure 6.2. Although P8 UCM is capable of simulating impoundments such as pond, reservoirs, wetlands, etc., the present analysis excluded the detailed representation of impoundments for two reasons. One is that the objective of the project is to develop hydrological targets for impaired watersheds in relation to attainment watersheds. This comparative exercise can eliminate the errors associated with the exclusion of impoundments if the selection of an attainment watershed for each impaired watershed is carefully conducted. The second reason for exclusion of impoundments is due to the lack of site-specific data.

Among the UVM gauges, Potash Brook was selected for detailed calibration. Potash Brook is one of the impaired watersheds with substantial urban development. Therefore evaluating the sensitivity of percent imperviousness is appropriate. Potash Brook has the least influence from water impoundments in the watershed among the UVM gauged watersheds. Thus, it is a suitable watershed to evaluate the impact of other model parameters. Also, Potash Brook is in close proximity to the Burlington Airport rainfall gauge, and it eliminates the uncertainty associated with the spatial variability of climate data.

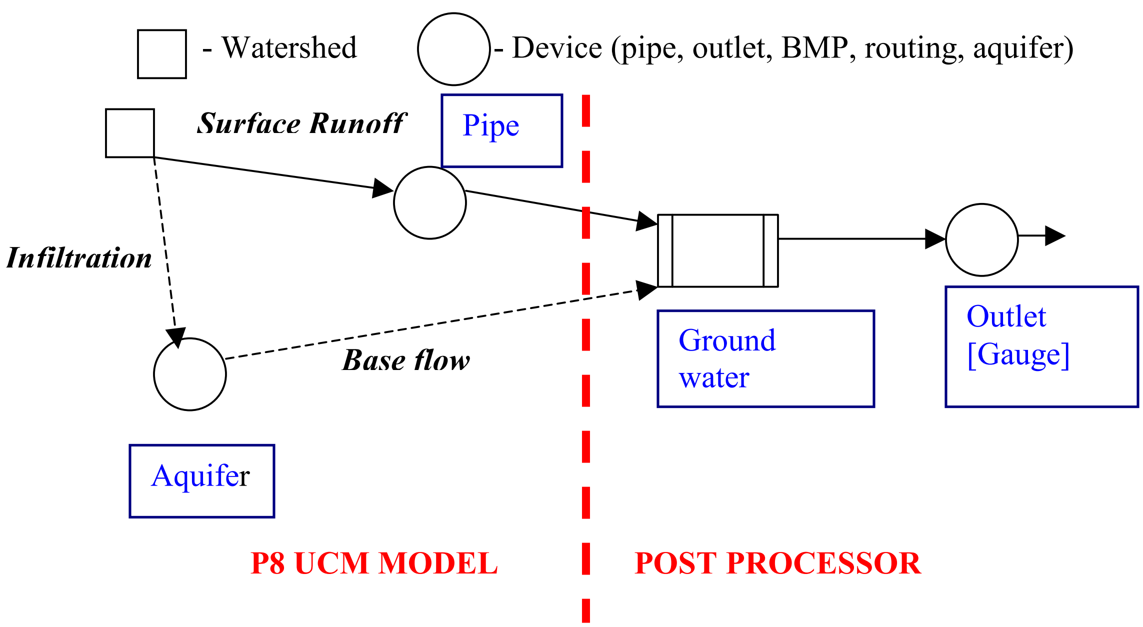

Figure 6.2. Sample schematic diagram for a selected gauge station.

6.2.1. Watershed Percent Imperviousness

In the SCS CN approach (SCS, USDA, 1969) runoff starts after an initial abstraction (Ia) of surface has been completed. This abstraction consists principally of interception, surface storage, and infiltration. SCS expressed Ia = 0.2 * (1000/CN – 10); CN – Curve Number. In Potash Brook, Pervious Curve Number (PCN: Average weighted CN for the pervious portion of the watershed) is 69 and the initial abstraction is 0.9 inches. In this watershed we can assume that the runoff generated by the storms, with a rainfall amount of less than 0.9 inches, is primarily generated by the impervious portion of the watershed. Therefore, a storm of 0.75 inches between 1:00 PM and 6:00 PM on 7/1/2004 was selected to examine PI.

As previously mentioned, P8 UCM has two input parameters that specifically relate to surface runoff from impervious areas, percent imperviousness (PI) and the Imperviousness Runoff Coefficient (IC). As part of the model calibration process, these parameters were evaluated to identify the most suitable values to be used in this study. The following are the values used for Potash Brook.

- PI = 22
- IC = 0.76 (for a mixed residential watershed following Lincoln Creek study in Wisconsin as presented in P8 UCM Help (Walker, 1990))
- IC = 0.54 (for a residential watershed following Monroe street study in Wisconsin as presented in P8 UCM Help (Walker, 1990))
- IC = 0.65 (as a mid point of 0.76 and 0.54)
- IC = 1.0 (fully connected imperviousness)

Figure 6.3 compares predicted hydrographs with observed data during the 7/1 storm. The combination of estimated PI with IC of 0.0.54 represents the condition in Potash Brook appropriately (Figure 6.4).

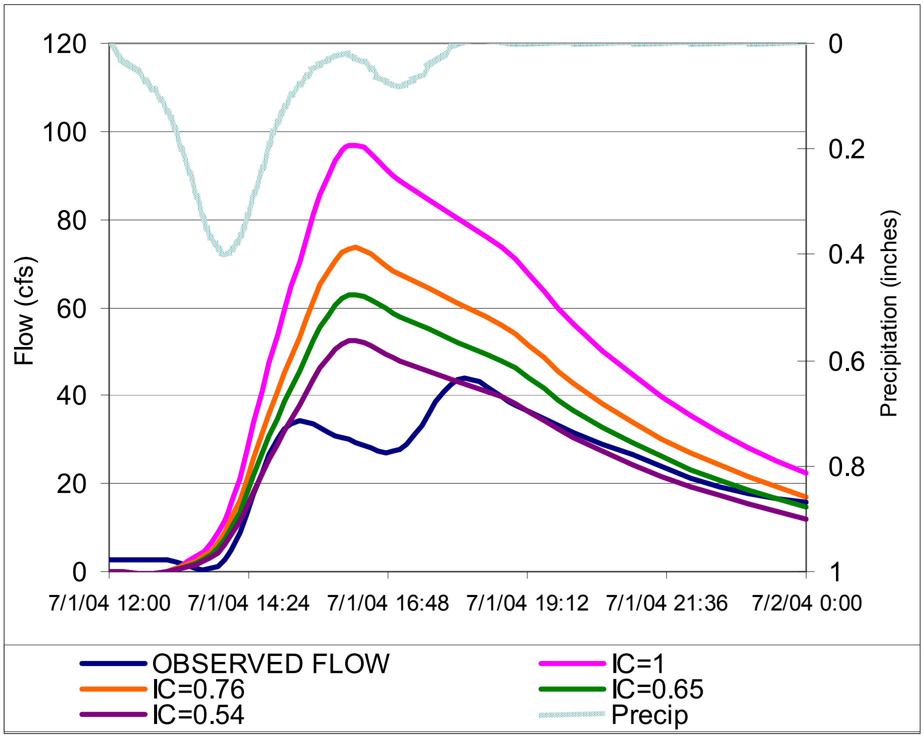

Figure 6.3. Precipitation and stream flow during the storm on 7/1/04.

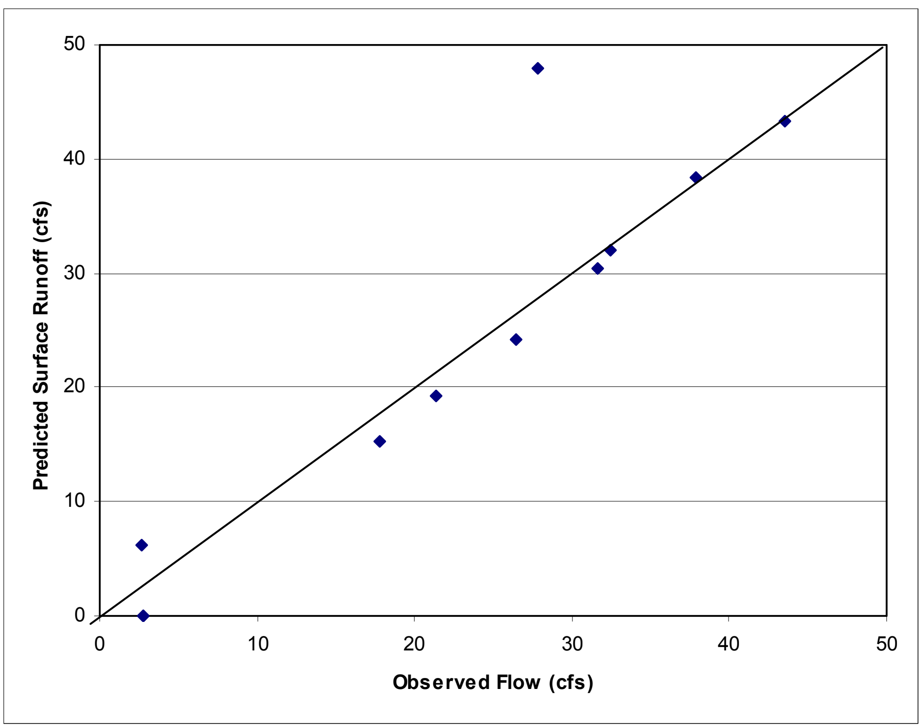

Figure 6.4. Predicted flow (PI = 22, IC = 0.54, R^2=0.78) and observed flow during the storm on 7/1/04. An ideal fit line is also plotted for an easy comparison.

To further understand the accuracy of IC, the peak flow for all storm events during July and August 2004 were compared with observed peak flow (Figure 6.5) and found that IC of 0.54 is well representing the conditions in Potash Brook.

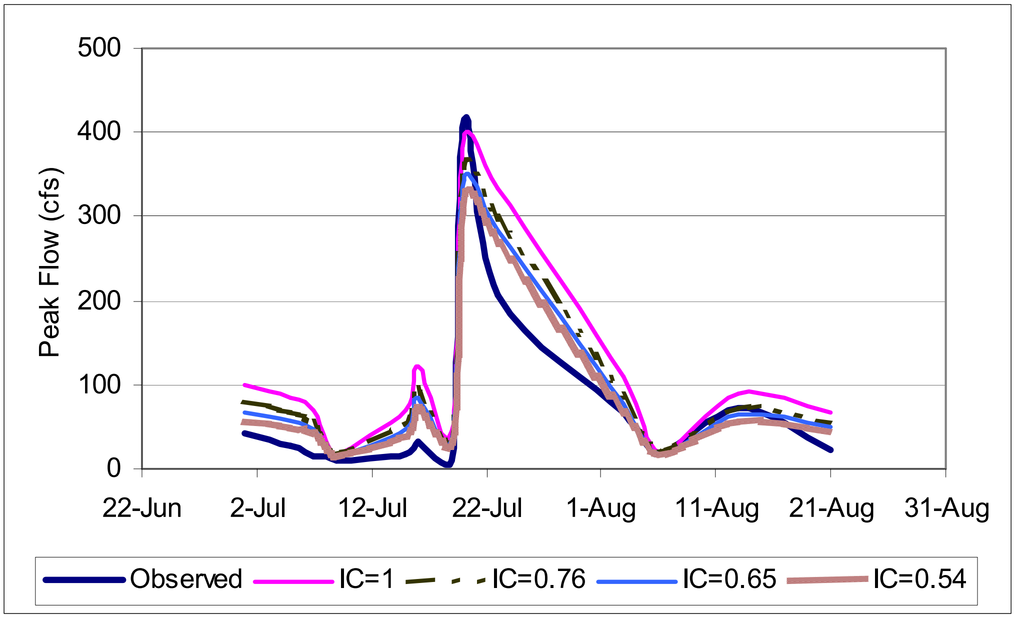

Figure 6.5. Predicted peak flow and observed flow for all storm events during July and August 2004

6.2.2. Pervious Curve Number

The methodology of estimating curve number using hydrological soil group and land use was developed by SCS (USDA, 1986) and widely used all over the country for many years. To understand the accuracy of estimating PCN using the methodology presented in Section 3 (Table 3.2), three different values of PCNs were evaluated: estimated PCN based on soil and land use following SCS, and PCNs ± 5 of estimated one. Predicted flow during two storms in July 2004 (1.68 inches –7/20 & 1.25 inches 7/22 – 7/23) was closely compared with observed flow and found that the estimated curve number predicts the flow reasonably (Figure 6.7). In this evaluation, PI and IC were kept the same for all three cases as 22 and 0.54, respectively.

Given that the uncertainties associated with grouping the land uses and soils, the methodology applied reasonably simulated the flow during the storm event. As a result, the approach was considered accurate enough for FDC development and application.

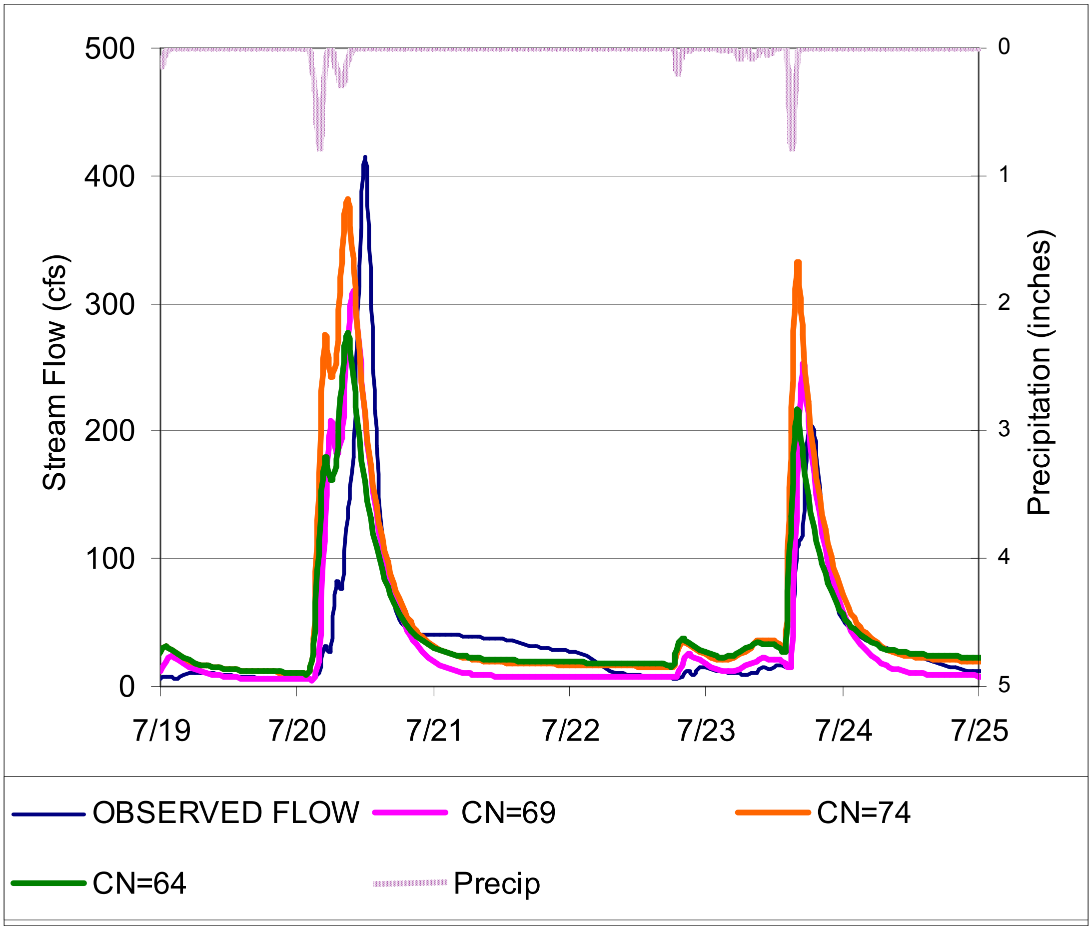

Figure 6.6. Predicted and observed flow during 7/19/04–7/25/04.

6.2.3. Surface Runoff Time of Concentration

TC-SR of 5, 10, and 15 hours were evaluated while the rest of the model parameters were kept the same. Comparison of simulated peak flow resulted in the coefficient of determinations (R^2) of 0.85, 0.92, and 0.95, respectively. Although TC-SR of 5 hours predicted the observed maximum flow well, it generally over-predicts the peak flow. On the other hand, TC-SR of 15 hours predicted well during many small storms and under-predicted peak flows during the large storms. It was observed that the TC-SR of 10 hours fits well in representing Potash Brook's conditions as presented in Figure 6.7. Predicted flow and observed flow for the rest of the UVM watersheds are plotted in Figures 6.8 through 6.12 by following the calibrated approach of Potash Brook.

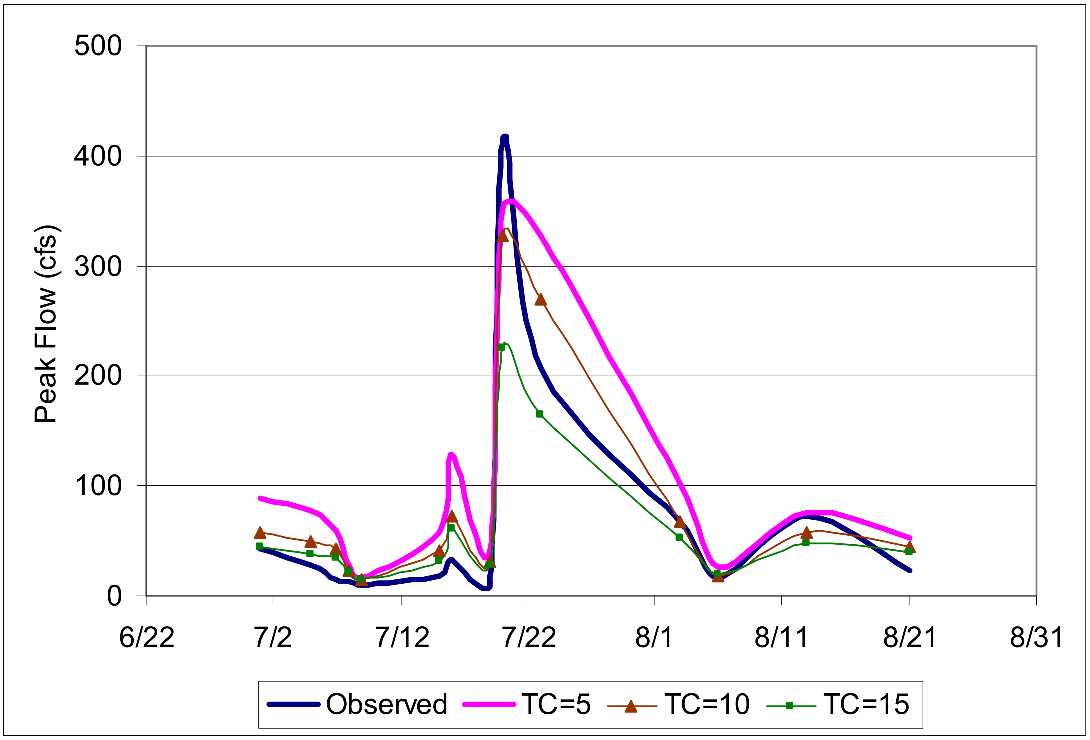

Figure 6.7. Observed and modeled peak flow (magnitude) at Potash Brook during storm events in July and August 2004.

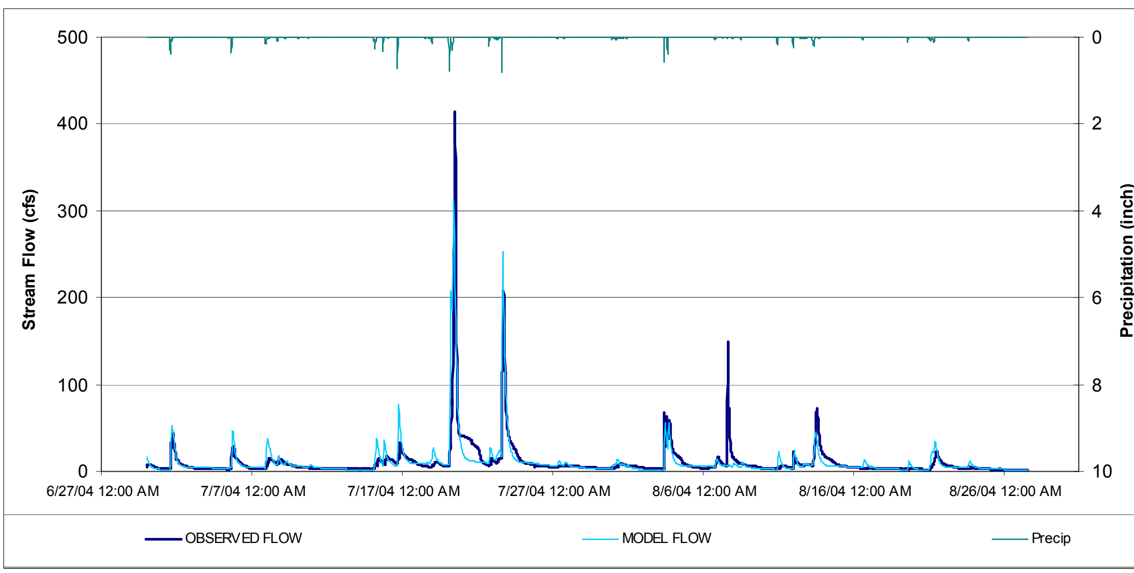

Figure 6.8. Predicted flow and observed flow during July and August 2004 (Potash Brook: TC=10, PI = 22, IC=0.54, PCN=69)

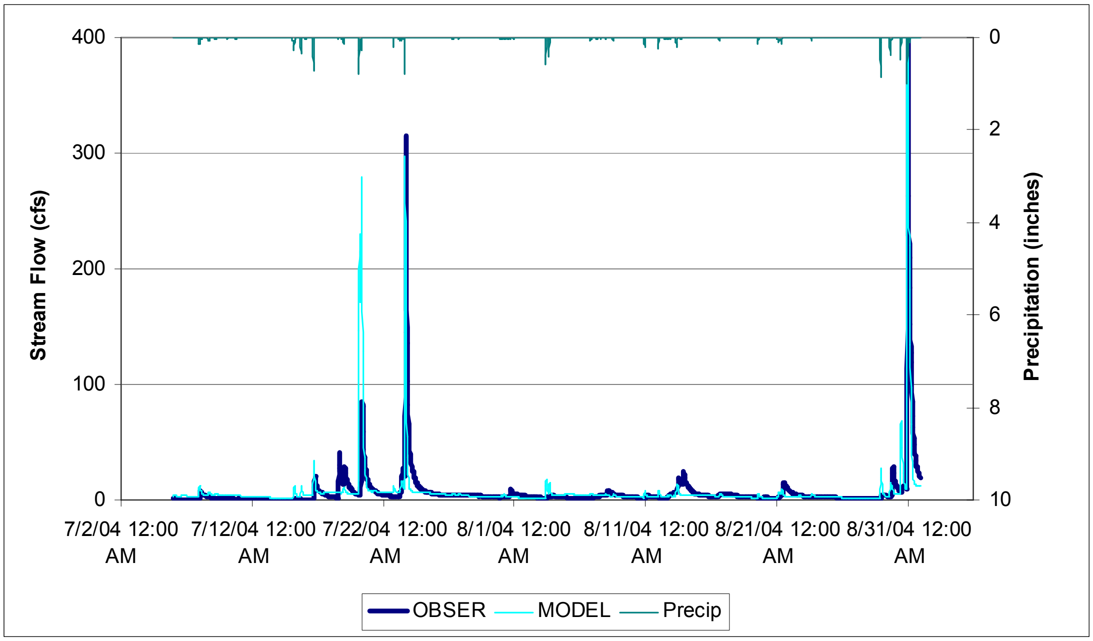

Figure 6.9. Predicted flow and observed flow during July and August 2004 (Johnnie Brook: TC=5, PI = 2, IC=0.54, PCN=76)

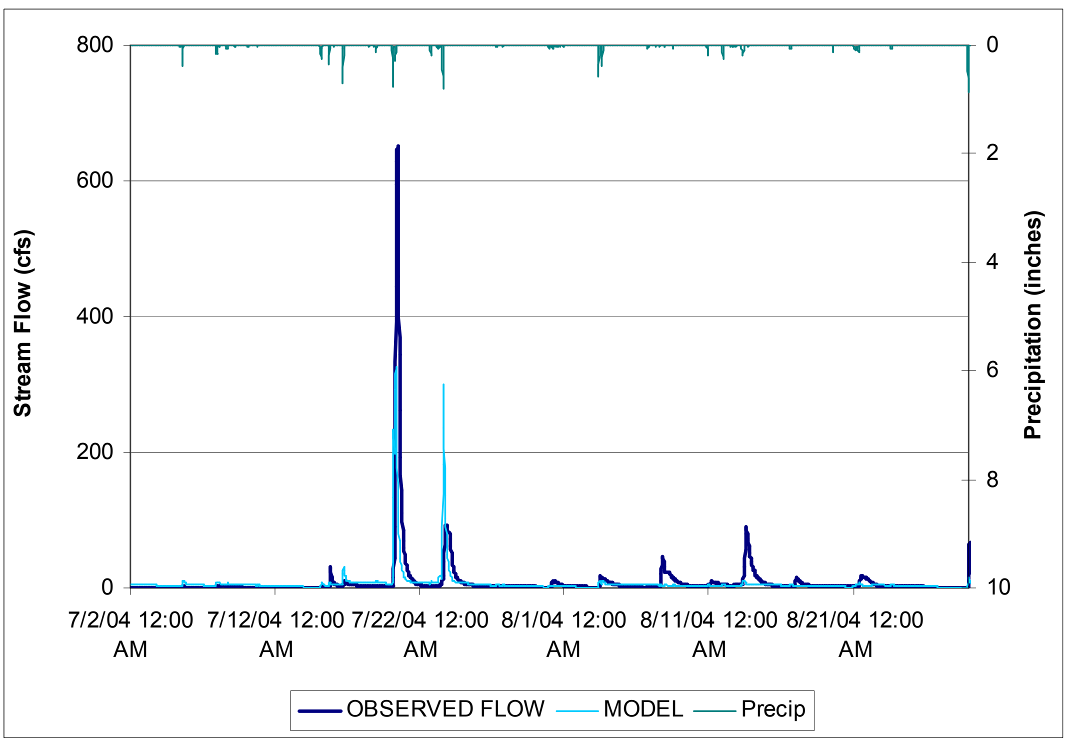

Figure 6.10. Predicted flow and observed flow during July and August 2004 (Monroe Brook: TC=8, PI = 9, IC=0.54, PCN=77)

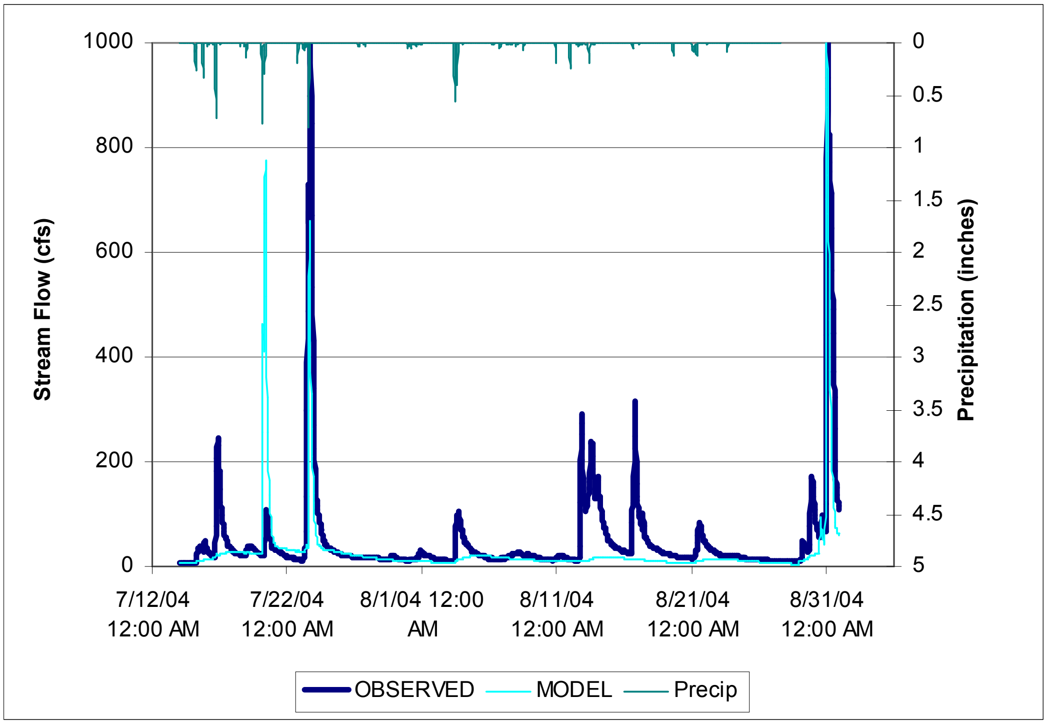

Figure 6.11. Predicted flow and observed flow during July and August 2004 (Mill Brook: TC=9, PI = 3, IC=0.54, PCN=70)

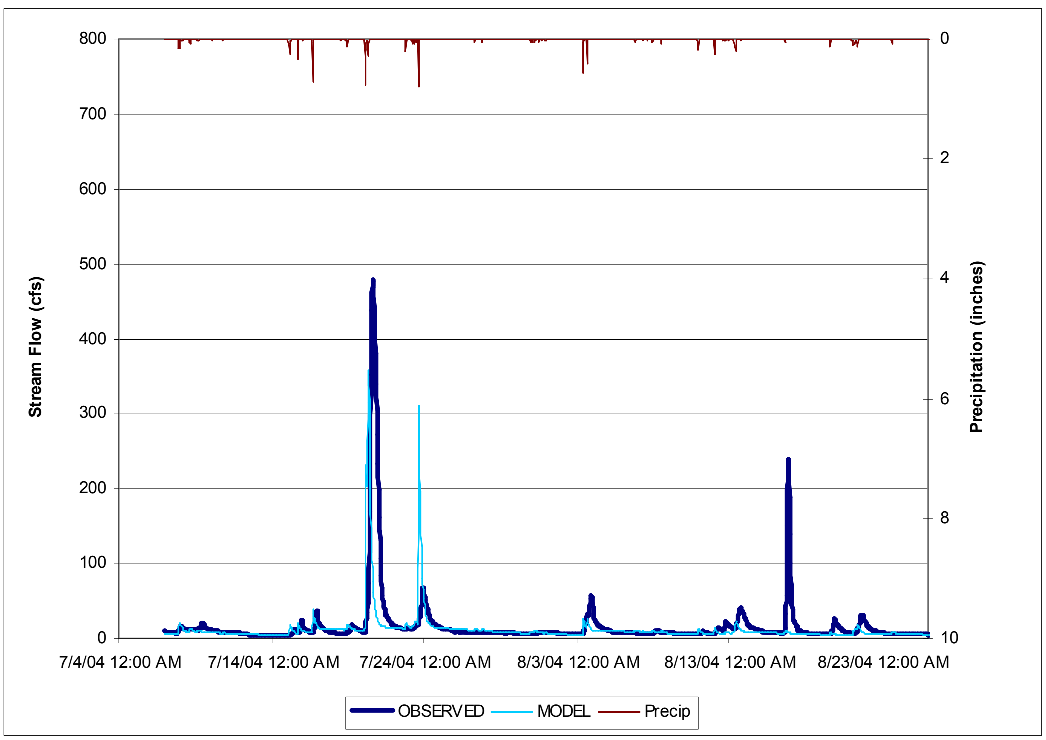

Figure 6.12. Predicted flow and observed flow during July and August 2004 (Indian Brook: TC=9, PI = 16, IC=0.54, PCN=73)

6.3. Estimation of Time of Concentration for Ungauged Watersheds

Appropriate TC-SR values for each UVM watershed were estimated through the calibration process. Unlike PCN and PI, there is no direct way of estimating TC-SR for ungauged watersheds. Therefore, it is important to develop a methodology for estimating TC. In general, TC is proportional to the watershed area. Thus, the relationship between TC and watershed area for the UVM watersheds were examined. Although TC increases with an increase in area, it exhibits relatively a poor correlation (Figure 6.13).

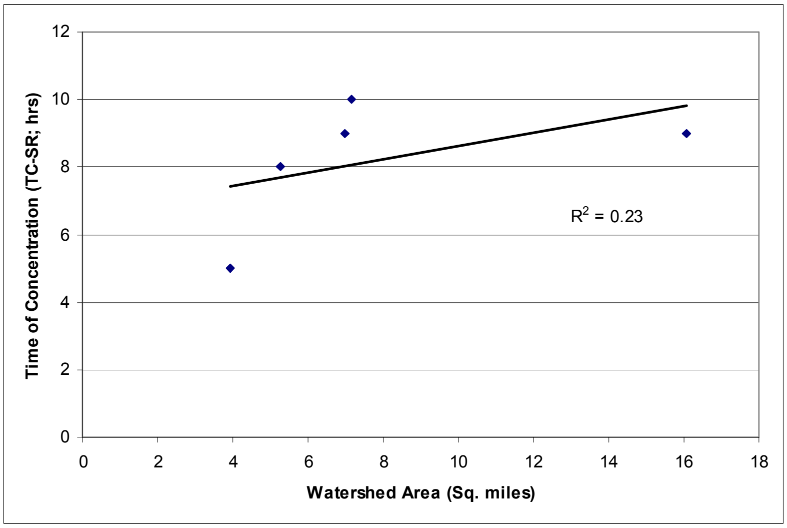

Figure 6.13. Relationship between TC-SR and watershed area.

Another watershed feature that influences TC is watershed slope. The relationship between TC and average watershed slope is presented in Figure 6.14. Although TC decreases with the increase in watershed slope, it also exhibits a poor correlation.

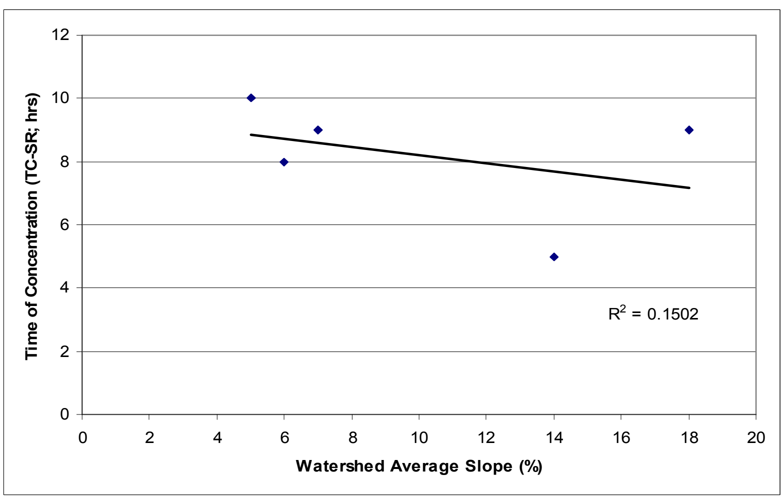

Figure 6.14. Relationship between TC and watershed average slope.

Because TC shows an increase with watershed area and a decrease with watershed slope, the relationship between TC and the ratio between area and slope (Area/Slope), was further examined and resulted in a satisfactory correlation (Figure 6.15).

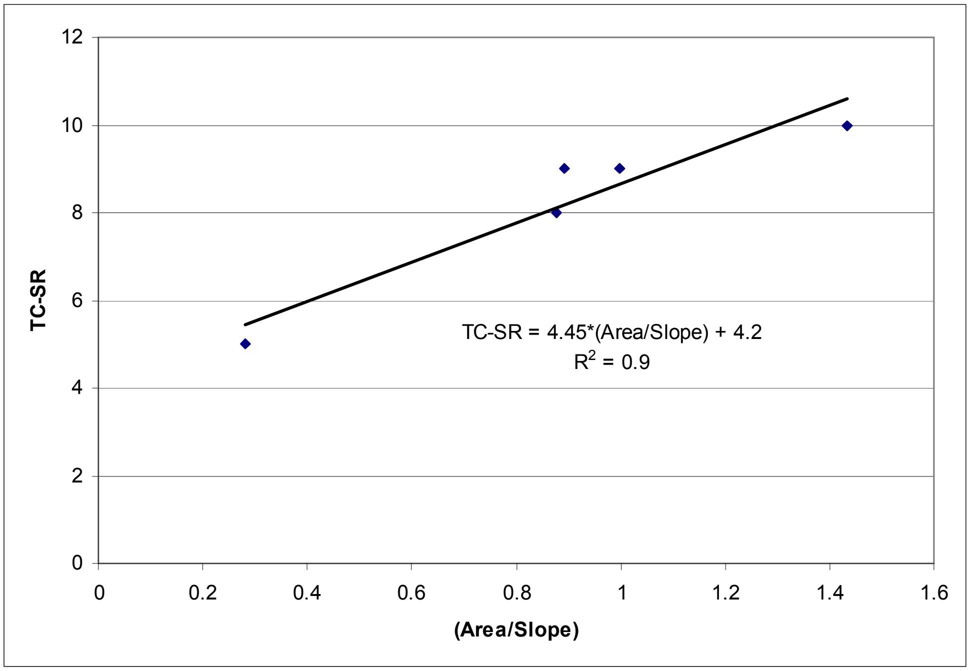

Figure 6.15. Relationship between TC and area-slope ratio.

The relationship [TC=4.45*(Area/Slope) + 4.2; Eq. 6.1] can be used to estimate TC for ungauged watersheds.

6.4. Calibration Results and Standard Procedures

Given the complexity of the watershed features and processes, it is apparent from model calibration that a simple representation of P8 UCM, with ground water improvement, simulates the stream flow reasonably well. Although the model being employed is not extremely detailed, it predicted the relative variability of stream flow among watersheds. The development of FDC and relative hydrological targets, especially the relative variability of stream flow between impaired and attained watersheds, can be carried out with reasonable confidence.

Using the calibration process, a standard procedure for model set up and simulation was developed as follows to develop time-series flow and flow duration curve for ungauged impaired and attainment watersheds.

1. Estimate the Percent Imperviousness using VCGI land use data and the coefficients given in Table 3.1.
2. Estimate Pervious Curve Number using VCGI land use data and VCGI SSURGO soil data (Table 3.2).
3. Estimate Surface Runoff Time of Concentration using Eq. 6.1. Watershed area and average watershed slope can be estimated using VCGI slope24 data.
4. Estimate Depression Storage using Table 3.3.
5. Set Impervious Coefficient as 0.54 as calibrated.
6. Set the ground water recession coefficient as 0.003 ($hour^{-1}$).
7. Use observed hourly precipitation and daily temperature data for the model.

7. MODEL APPLICATION

7.1. FDC Development

FDC shows the percentage of time during a period of record that flow exceeds a certain flow value. The median flow is exceeded 50 percent of the time. The two extremes can be represented by the 95th percentile (low flow) and 5th percentile (high flow) exceedance flows. One-year 24-hour design average flow is approximately exceeded 0.03 percent of the time. Because actual flow rates can vary considerably among watersheds, they are normalized by watershed area or median flow to facilitate cross-comparison.

The P8 UCM model with ground water enhancement was applied to develop time-series flow and flow duration curve for ungauged impaired and attainment watersheds. The simulation was carried out using 12 year (01/1988–12/1999) climate data and the stream flow was generated using P8 UCM model and ground water tool. The initial 2-year simulations were dropped to eliminate the uncertainties associated with initialization errors. Simulated flow for 10 years (01/1990–12/1999) were used to develop FDC. FDC for selected watersheds are presented in Figures 7.1 through 7.4. Table 7.1 presents several points along FDC for selected watersheds.

Initial evaluation of FDC revealed that there were differences, in general, between impaired and attainment watersheds as it appears a red and a blue band in Figures 7.1 a and b. The impaired watersheds have higher flood flow and lower base flow than that of attainment watersheds. However, a detailed look at FDC further revealed that the flow characteristics of a few impaired watersheds match well with the pack of attainment watersheds and vice versa. For example, the Sunderland Brook is an impaired watershed, but FDC is similar to that of many attainment watersheds. This is attributed to the fact that the Sunderland brook has higher infiltration capability with a PCN of 51 than that of the rest of the impaired watersheds with PCNs in the 70s. This illustrates the importance of identifing appropriate attainment watershed(s) for every impaired watershed on the basis of the respective watershed characteristics.

Table 7.1. Selected statistical points along FDC based on 10-year hourly flow simulations. The data in red (normal font) and blue (italic fond) represent impaired and attainment water bodies respectively.

Water Body	Stream Flow (cfs/sq. miles)							
	0.10%	0.30%	1%	5%	20%	50%	80%	95%
Allen Brook	22.67	11.74	6.18	3.61	2.08	1.15	0.546	0.202
Bartlett Brook	18.23	11.35	7.10	3.78	2.15	1.16	0.548	0.2
Centennial Brook	24.38	16.12	9.22	4.13	2.14	1.13	0.522	0.188
Englesby Brook	24.71	15.73	8.98	4.03	2.12	1.13	0.527	0.194
Indian Brook	21.77	11.16	6.1	3.63	2.08	1.15	0.548	0.202
Morehouse Brook	25.98	16.90	9.49	4.15	2.15	1.12	0.512	0.195
Munroe Brook	23.88	11.98	6.03	3.55	2.05	1.14	0.543	0.201
Potash Brook	20.43	12.25	7.42	3.91	2.16	1.15	0.536	0.197
Sunderland Brook	11.03	8.27	6.54	3.82	2.29	1.26	0.602	0.223
Alder Brook	*19.96*	*11.02*	*6.08*	*3.77*	*2.19*	*1.22*	*0.585*	*0.218*
Allen Brook (Attained)	*21.13*	*11.20*	*6.07*	*3.75*	*2.17*	*1.21*	*0.581*	*0.237*
Sand Hill Brook	*9.10*	*8.03*	*6.38*	*3.81*	*2.33*	*1.29*	*0.617*	*0.234*
Youngman Brook	*8.96*	*7.90*	*6.18*	*3.74*	*2.29*	*1.29*	*0.61*	*0.229*
Little Otter Creek	*15.55*	*9.03*	*5.92*	*3.79*	*2.23*	*1.25*	*0.601*	*0.225*
Mallett Creek	*19.11*	*10.93*	*6.04*	*3.75*	*2.18*	*1.22*	*0.584*	*0.218*

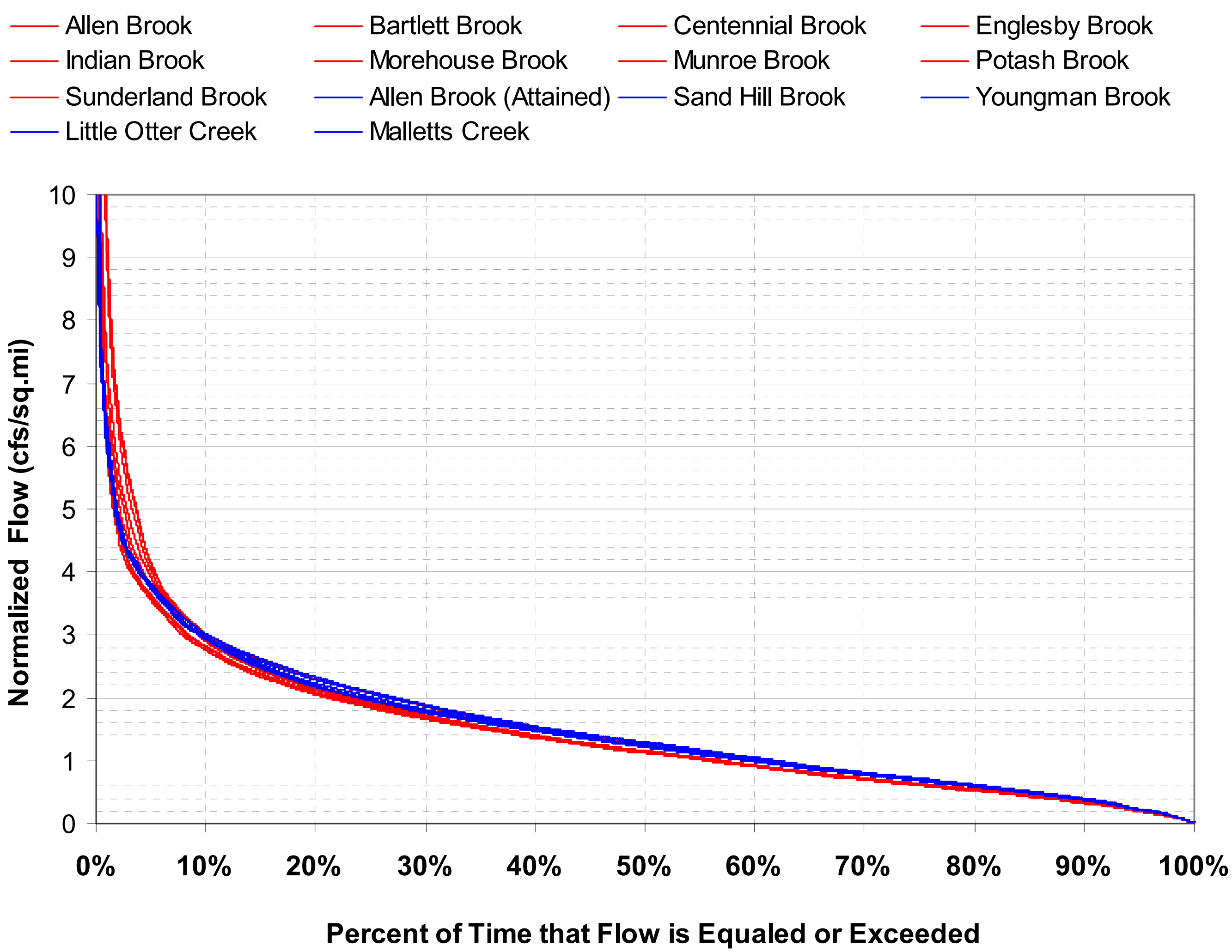

Figure 7.1. Flow duration curves for impaired (red) and attainment (blue) water bodies.

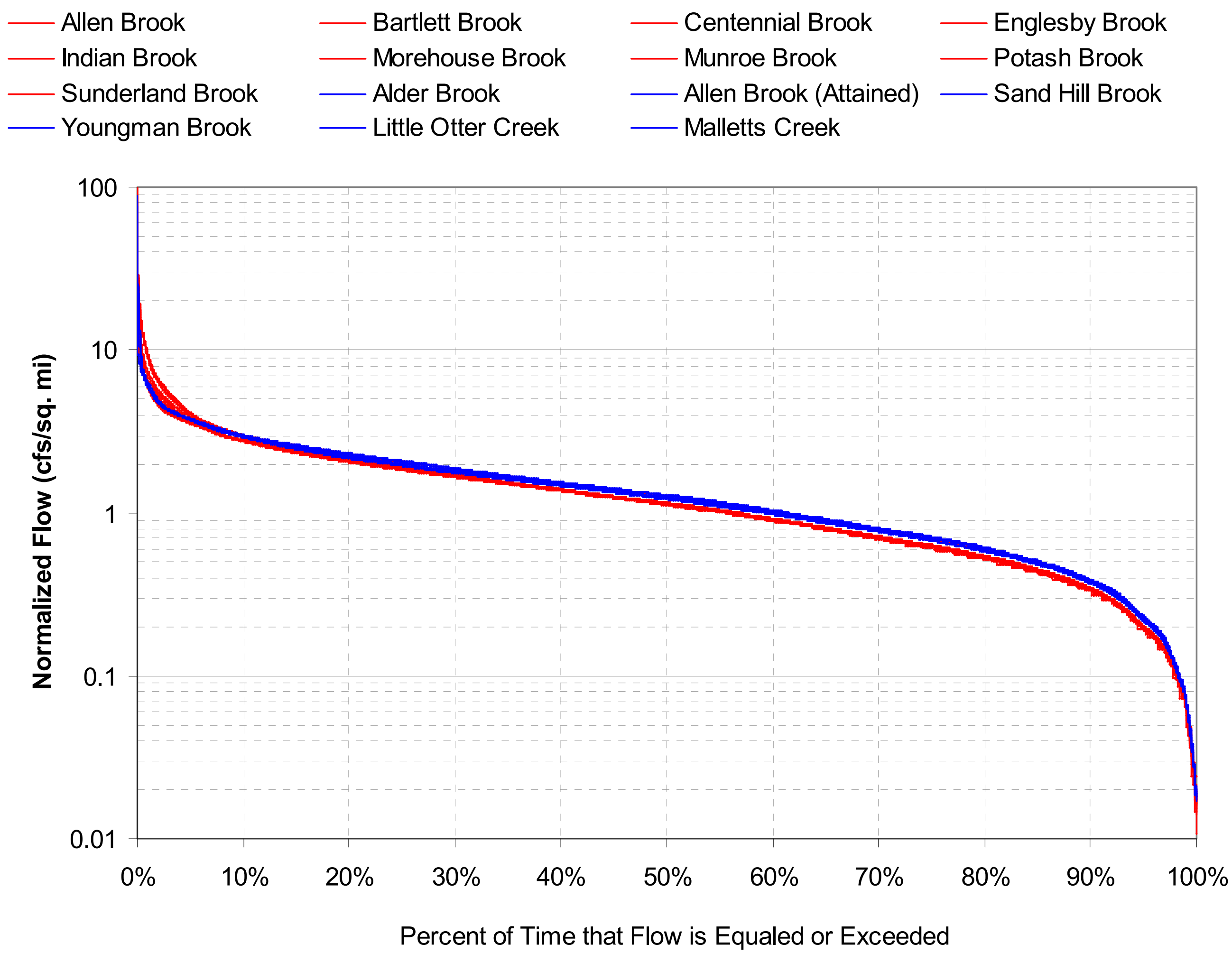

Figure 7.2. Flow duration curves for impaired (red) and attainment (blue) water bodies in log scale.

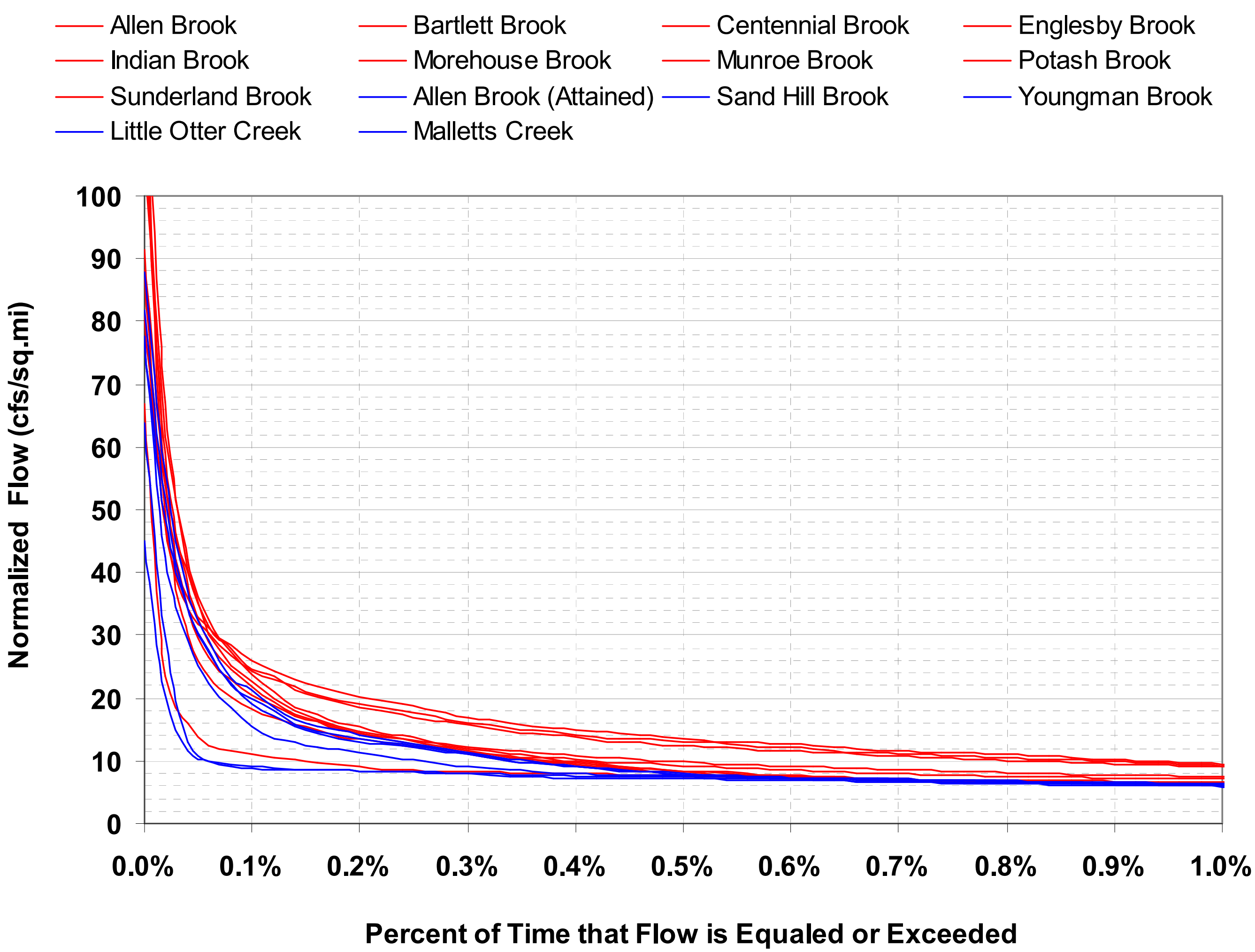

Figure 7.3. Flow duration curves for impaired (red) and attainment (blue) water bodies in the flood flow (high flow) domain.

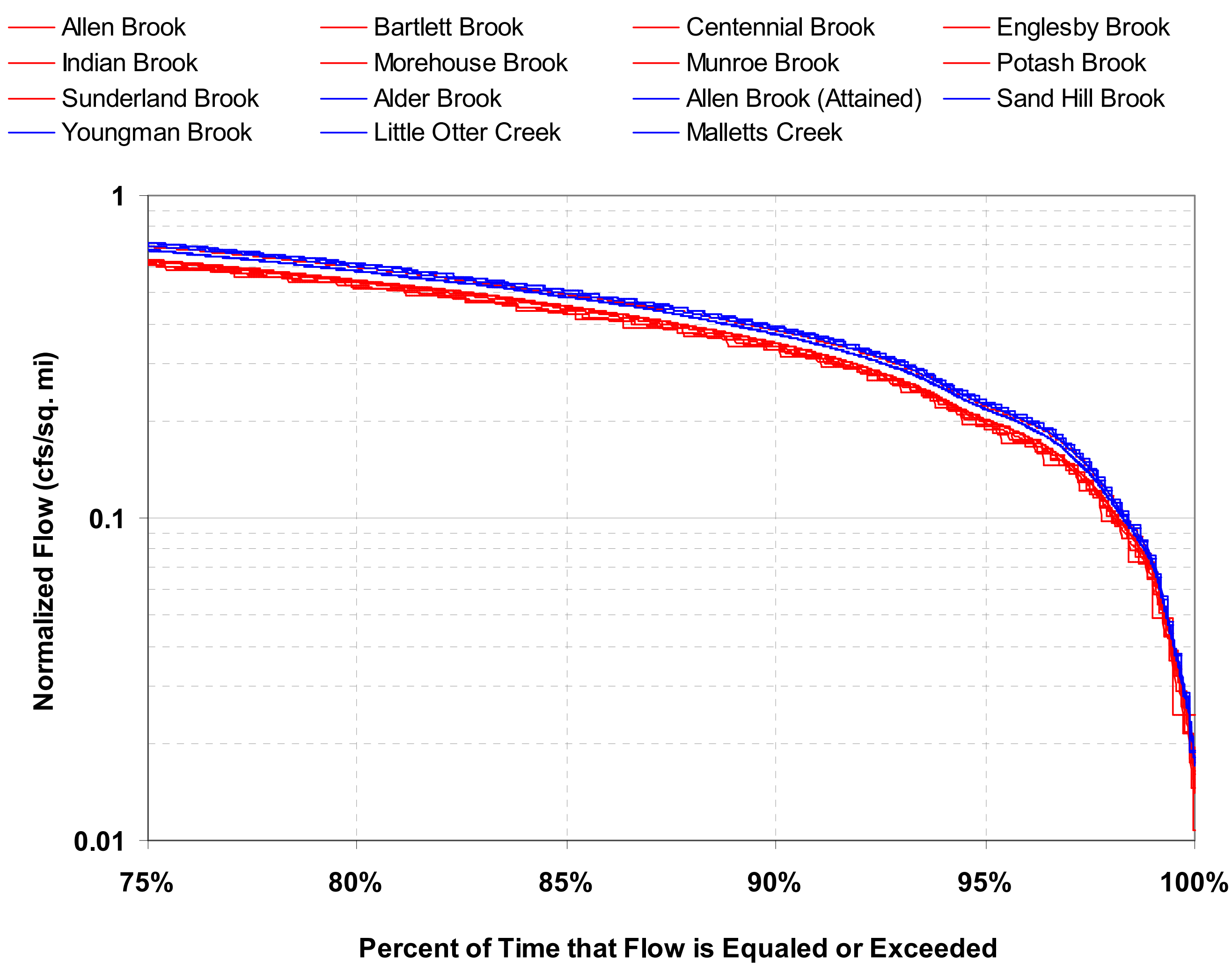

Figure 7.4. Flow duration curves for impaired (red) and attainment (blue) water bodies in the base flow (low flow) domain.

7.2. Design Storm Analysis

Selecting and setting stormwater control targets using FDC help to address the issues related to both dry and wet weather events for conditions over a long-term period. While stressing the importance of addressing the issues associated with the entire hydrological domain, it is important to understand the control measures during the storm events, especially with a focus on implementing stormwater management solutions. The design and construction practices follow guidance and standards that are primarily set by the design storm events. This section presents the results of model simulation of a one-year 24-hour design storm to enhance the understanding of control targets.

SCS Type II 24-hour 1-year design storm (2.1 inches for Chittenden County) was applied to four selected watersheds, three impaired (Centennial, Sunderland, and Potash Brooks) and one attainment (Mallet Brook), and the stream flow were simulated and the results are presented in Figures 7.5 and 7.6 and Table 7.2. The magnitude of peak and the volume of surface runoff and stream flow are substantially higher for the impaired watershed than that of the attainment watershed. This comparison presents another added application of developed P8 UCM model to help select and set the stormwater control measures for impaired watersheds.

Table 7.2. Simulated runoff and stream flow during a one-year 24-hour SCS Type II design storm. Rainfall is in inches and surface runoff and stream flow are in cfs/sq. miles.

Hour	Rain	Centennial		Mallet		Potash		Sunderland	
		Surface Runoff	Stream Flow	Surface Runoff	Stream Flow	Surface Runoff	Stream Flow	Surface Runoff	Stream Flow
1	0.02	0.19	0.19	0.01	0.01	0.07	0.07	0.06	0.06
2	0.03	0.81	0.91	0.06	0.18	0.32	0.43	0.27	0.38
3	0.03	1.49	1.71	0.11	0.38	0.64	0.87	0.50	0.75
4	0.03	1.98	2.31	0.16	0.56	0.91	1.27	0.67	1.05
5	0.03	2.46	2.92	0.21	0.76	1.19	1.68	0.84	1.36
6	0.03	2.88	3.50	0.26	0.99	1.46	2.12	0.99	1.69
7	0.04	3.32	4.11	0.31	1.23	1.75	2.57	1.14	2.02
8	0.04	3.76	4.74	0.37	1.52	2.04	3.08	1.30	2.40
9	0.06	4.34	5.53	0.43	1.81	2.39	3.63	1.50	2.83
10	0.07	5.29	6.75	0.52	2.22	2.89	4.43	1.82	3.46
11	0.12	7.07	8.88	0.67	2.78	3.74	5.65	2.43	4.46
12	0.9	25.24	27.63	1.95	4.74	10.86	13.38	8.40	11.09
13	0.24	37.20	44.38	3.07	11.46	17.09	24.66	12.55	20.62
14	0.1	30.28	38.62	2.99	12.75	16.26	25.07	10.49	19.87
15	0.07	22.64	31.41	2.82	13.08	14.31	23.58	8.05	17.93
16	0.05	16.80	25.79	2.68	13.19	12.38	21.88	6.12	16.24
17	0.05	12.69	21.83	2.58	13.26	10.69	20.34	4.71	15.00
18	0.04	9.80	19.07	2.50	13.29	9.23	19.00	3.69	14.11
19	0.03	7.71	17.05	2.42	13.28	7.96	17.82	2.93	13.44
20	0.03	6.21	15.59	2.33	13.23	6.89	16.80	2.37	12.93
21	0.03	5.07	14.49	2.23	13.16	5.96	15.90	1.94	12.53
22	0.03	4.23	13.65	2.14	13.04	5.18	15.13	1.62	12.21
23	0.03	3.69	13.11	2.07	12.96	4.57	14.51	1.40	11.99
24	0.02	3.30	12.72	2.02	12.89	4.07	14.00	1.24	11.83
30	0	0.28	9.09	0.61	10.77	1.15	10.44	0.13	10.03
36	0	0.02	8.16	0.17	9.56	0.31	8.90	0.01	9.17
42	0	0.00	7.53	0.05	8.73	0.08	8.02	0.00	8.46
48	0	0.00	6.96	0.01	8.04	0.02	7.36	0.00	7.82
54	0	0.00	6.43	0.00	7.42	0.01	6.79	0.00	7.23
60	0	0.00	5.95	0.00	6.86	0.00	6.28	0.00	6.68
66	0	0.00	5.50	0.00	6.34	0.00	5.80	0.00	6.18
72	0	0.00	5.08	0.00	5.86	0.00	5.36	0.00	5.71

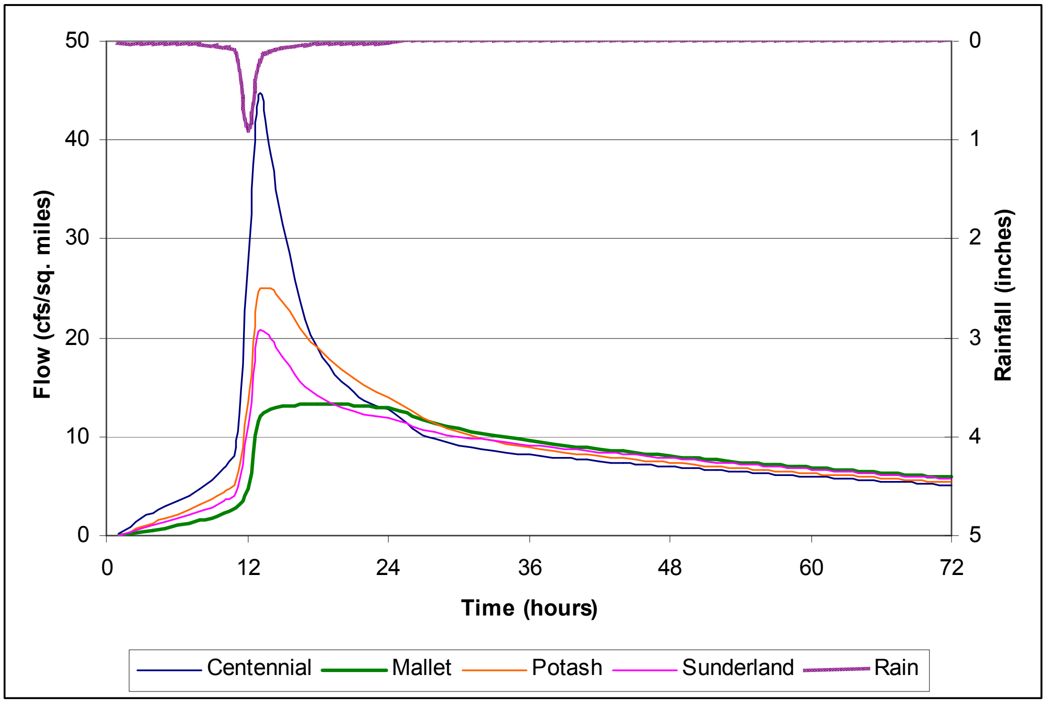

Figure 7.5. Model simulated stream flow during a one-year 24-hour design storm.

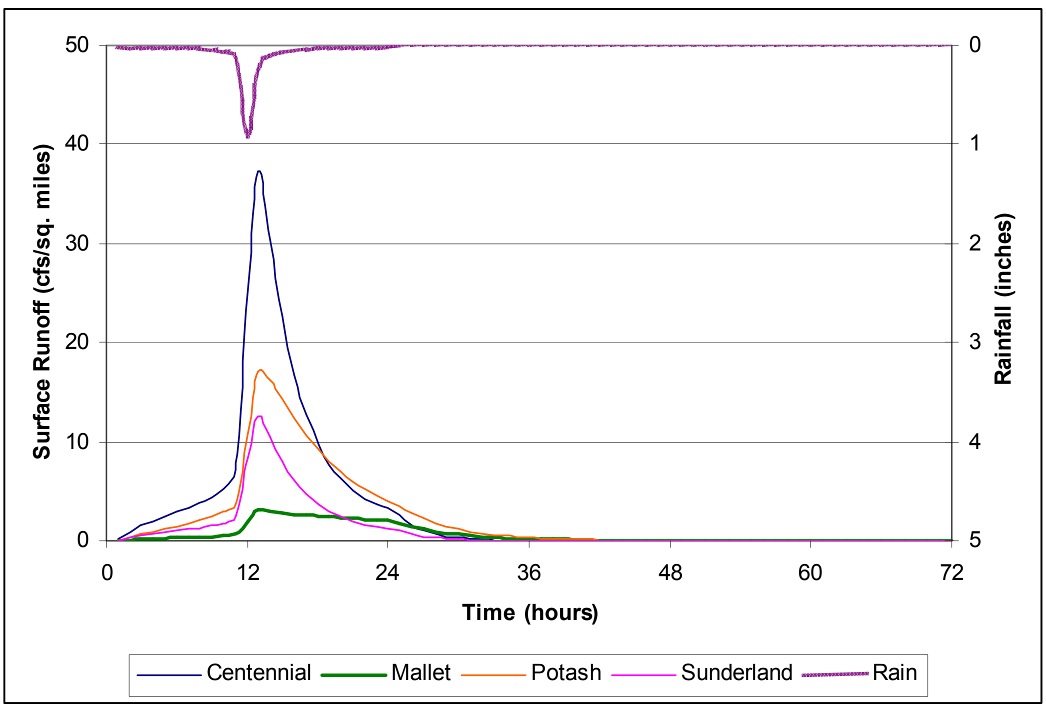

Figure 7.6. Model simulated surface runoff during a one-year 24-hour design storm.

8. CONCLUSION AND DISCUSSION

The state's ultimate goal is to restore the impaired watersheds to achieve water quality standards. To achieve this goal, the state decided to use watershed hydrology as a surrogate indicator to identify appropriate control measures or targets for each impaired watershed, subject to aquatic life impairments due to stormwater runoff. The idea is to compare FDC of each impaired watershed to an attainment (reference) watershed or a set of attainment watersheds and identify control targets.

In the absence of long-term flow records to generate FDC, a computer model was needed to fill the data gap. The P8 UCM model was selected as a compromise for many factors such as the scientific objectives of the present study, the number of watersheds for which analysis is required, available budget, and the intended future use of the models by the state.

A detailed model calibration with daily and hourly flow observations and a ground water enhancement to the existing P8 UCM model was carried out and a standard of procedures was developed to apply the model to all ungauged watersheds. Given the complexity of the watershed features and processes, it is apparent from model calibration that a simple representation of P8 UCM, with ground water improvement, simulates the stream flow reasonably well. Although the model being employed is not extremely detailed, it predicted the relative variability of stream flow among watersheds. It supports the development of FDC and relative hydrological targets, especially the relative variability of stream flow between impaired and attained watersheds, with reasonable confidence.

Calibrated models were applied to develop FDC for selected watersheds to demonstrate the model capability and to set the stage for the next steps, selecting appropriate target for each impaired watershed. This application revealed the importance of appropriate selection of closely matched attainment watershed(s) for each impaired watershed. The model also applied to evaluate the watershed responses during storm events. It is an important application, especially in design and implementation stages of restoration efforts. Overall, the developed model is capable of both event based and long-term hydrological simulations for relative variability among watersheds and drainage areas.

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